PRODUCTIVITY AND SUSTAINABILITY OF INTERCROPPING SYSTEMS IN THE NORTHERN GREAT PLAINS

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DOCTOR OF PHILOSOPHY

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ABSTRACT

The sustainability and productivity of cropping systems in the northern Great Plains is at risk because food, feed, and energy are produced mainly in very short crop rotations or monocultures. High input agriculture and lack of crop diversity has led to negative environmental impact either on- or off-site. Diverse cropping systems can reduce the need of external inputs such as fertilizer, decrease water pollution, reduce soil erosion, and improve land use efficiency, and resilience. The first study had the objective to determine the most resilient system to produce silage and biogas including monocultures and intercropping of maize (*Zea mays* L.) and forage sorghum (FS) [*Sorghum bicolor* (L.) Moench]. The results indicated that non-BMR (brown mid-rib) FS monocultures and maize-FS mixed cultures produced similar or higher biomass and biogas yield compared with maize monocultures. Intercropping resulted in a higher quality forage compared with FS monocultures. Within-row and inter-row intercropping of FS with maize is a promising alternative to maize silage, improving resiliency without compromising forage yield and quality. The second study focuses on the agronomic performance of winter camelina [*Camelina sativa* (L.) Crantz.] intersown as a cover crop into standing soybean [*Glycine max* (L.) Merr] or maize. Camelina sown on the same date as maize or soybean resulted in lower grain and biomass yield of both crops indicating that intersowing should be done after V3-V5 stages. The economic analysis indicated camelina broadcast seeding into soybean had higher net revenue compared with camelina intersown in maize. Winter camelina winter hardiness and nutrient scavenging makes it a crop with good potential as cover crop in maize-soybean systems in the US Midwest. The environmental impacts of 11 cropping systems involving late-season cover crops, intercropping, intersowing cover crops into standing cash crops, and current cropping systems in the North Central US was evaluated. Global warming

potential was the highest in all systems that had maize, except for the maize-FS silage system. Including a cover crop in a system, resulted in higher CO_2 emissions, due to additional inputs. Further research is needed to evaluate the long-term benefits and ecosystem services of cover crops.

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TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

LIST OF APPENDIX TABLES

CHAPTER 1. INTRODUCTION

Today's world is facing a set of new challenges. As the global population and wealth of the people increases, the demand for food (cereals, legumes, roots, vegetables, meat, dairy, and fish) will likely increase adding pressure to the existing food supply systems (Godfray et al., 2010). World population will grow from 6 billion people in 2000 to 8 billion in 2025 to around 9.2 billion by the year 2050 (Khush, 2005; UNFPA, 2007). However, during the past five decades the amount of arable land devoted to food production increased by 9% while the food production has more than doubled (Godfray et al., 2010). Competition with other land uses such as urban and infrastructure development, and forest conservation, will hinder bringing new land into crop production (Evans, 2009).

In order to face the challenge of feeding an increasing world population and to fulfill other land use needs, the productivity per unit area of currently available land needs to be increased (Gregory and George 2011; Gesch et al., 2014). The northern Great Plains of the USA (NGP) comprising mainly the states of North Dakota, Minnesota, South Dakota and northern Iowa is a major food producing area in the USA (NASS, 2015). One potential way to increase land productivity and diversity in the NGP is with double cropping, unfortunately the short growing season limits the available crops for double cropping. Introducing a winter annual oilseed or an annual forage/biomass crop into existing cropping systems has resulted in improved land productivity while increasing diversity (Gesch et al., 2014; Berti et al., 2015), reducing soil erosion and nutrient losses (Krueger et al., 2012), and increasing sources of pollen for pollinators and wildlife habitat (Eberle et al., 2015).

Double, relay or intercropping of an oilseed and biomass crops such as camelina [*Camelina sativa* (L.) Crantz.] or forage sorghum [*Sorghum bicolor* (L.) Moench] into existing soybean- [*Glycine max* (L.) Merr.] and maize- (*Zea mays* L.) based rotations can increase crop productivity per unit of land area, improving the energy efficiency of the system (Berti et al., 2015), and also can be used as forage or lignocellulosic feedstock for biofuels (Heaton et al., 2013). Relay cropping is a type of intercropping described as growing two or more crops simultaneously on a single field for part of their growth cycle in a season (Gallagher, 2009). Intercropping improves the efficiency of resource utilization (Seran and Brintha, 2010), diversity (Lin, 2011), and stability and resilience of the system compared with a crop monoculture (Gaudin et al., 2015).

Cropping system diversification also can be achieved with cover crops increasing crop system resilience to a number of environmental stresses (Gaudin et al., 2013). Cover crops may reduce the need for in-season application of fertilizer (Mihailovic et al., 2006; Newman et al, 2007; Samarappuli et al., 2014; Ketterings et al., 2015), thus significantly reducing the production costs. Further, cover crops will provide other benefits to the cropping system such as enhanced soil health, reduced soil erosion, increased soil organic matter content, weed suppression, and other ecosystem services (Fisk et al., 2001; Mihailovic et al., 2006; Verhallen et al., 2012).

According to Bich et al. (2014), in the dryland areas of the U.S. western Corn Belt, planting a cover crop in maize production systems is challenging due to narrow windows for establishment, and limited soil water availability. As a result, the practice of intersowing a cover crop into a standing crop is becoming popular (Roth et al., 2015), especially in areas with a short growing season where planting a cover crop after the cash crop has been harvested is not an option. Late-season cover crops can significantly reduce N leaching from fields (Snapp et al., 2005), P run-off, and soil erosion (Bich et al., 2014). The most common cover crop in the NGP after maize and before soybean is winter cereal rye (*Secale cereale* L.), mainly because it is the only cover crop that consistently survives the harsh winters providing cover in both late fall and spring (Groff, 2015). Nitrogen uptake of 50 kg N ha^{-1} were reported with early fall seeding (Ort et al., 2014).

Broadleaf cover crops do not survive most winters in the NGP even when drilled after wheat (*Triticum aestivum* L.), thus looking for a new winter hardy broadleaf cover crop that survives the winter is necessary. Winter camelina has been evaluated in relay cropping with soybean (Gesch et al., 2014, Berti et al., 2015). Winter camelina is very winter hardy and requires vernalization to flower (Putnam et al., 1993). These two characteristics make camelina a great candidate as a cover crop for intersowing in standing maize or soybean, and it will survive the subsequent winter. It does not bolt even if intersown in the summer and survive most winters (Grady and Nleya, 2010; Gesch and Cermak, 2011).

Forage productivity in rainfed areas is very variable. Silage, mainly from maize, is the most important forage for dairy cattle (*Bos taurus* L.) because of the high productivity and forage quality per unit area (Coulter, 2008). However, maize requires a lot of water (Undersander et al., 2010) and in years with below normal rainfall, forage yield decreases (Hamilton et al., 2015). Resiliency of forage production systems is important in areas where summer rainfall might not be sufficient for maize silage production. Forage sorghum is much more tolerant to drought than maize but its forage quality is lower (Undersander et al., 2010). Maize silage productivity is higher than that of forage sorghum if water is available, but if water is scarce then forage sorghum productivity surpasses maize. Although it is unlikely that dairy farmers will replace maize silage with forage sorghum, there is the alternative of intercropping maize and forage sorghum to increase system resiliency. A mixed maize-forage sorghum system will have more stable yields in the long-term.

European countries, where production of bioenergy from biogas is a main focus, forage sorghum recently has gained attention as a novel feedstock crop (Negri et al., 2014; Windpassinger et al., 2015). Biogas, composed mainly of CH_4 and CO_2, is obtained by anaerobic digestion of organic matter, which can then be converted into electricity (Weiland, 2010). Maize silage is the principal substrate used in biogas production since maize currently has the highest dry matter and methane yield (Herrmann, 2013). Forage sorghum as a bioenergy crop has the ability to be integrated into many production areas and cultivation systems and requires less water, and N fertilizer than maize to obtain a high biomass yield (Rooney et al., 2007, Bean and Marsalis, 2012). A mixed maize-forage sorghum system will likely have higher biogas yields with fewer inputs.

Agricultural production in the NGP changed in the last two decades mainly due to higher prices, until 2013, and availability of early-maturing cultivars (Wolfram and Michael, 2009; Weise, 2013). As a result maize and soybean acreages have increased (NASS, 2015). The intensification of row crops has caused a dramatic reduction in crop biodiversity (Aguilar et al., 2015), increase of greenhouse gases (GHG) emissions, nutrient leaching and run-off (Robertson et al., 2014), water shortages due to over extraction (Evans, 2009), soil degradation (Zhang et al., 2007), and the disruption of the ecosystem (Nellemann et al., 2009). Ecosystem services are functions provided by the environment that benefit humans and they can be classified as provisioning, regulating, supporting, or cultural services (Millennium ecosystem assessment, 2005; Kragt and Robertson, 2014; Schipanski et al., 2014).

Life cycle assessment (LCA) is considered as a methodology to evaluate potential environmental impacts of a product or a production system (Buratti and Fantozzi, 2010). Currently, LCA is extensively used for evaluating the sustainability of bioenergy and food production systems (Tidaker et al., 2014). A LCA assessment consists of four major components: goal and scope definition, inventory analysis, impact assessment, and interpretation (Petre et al., 2013). During the impact assessment phase, both direct impacts to the environment, and indirect effects to human health, ecosystem health, and resources are categorized and evaluated (Petre et al., 2013).

This research evaluated different cropping systems with the objective of optimizing food and forage production while protecting the environment. The specific objectives were: (1) Evaluate the resiliency of maize-forage sorghum intercropping systems for both forage and biogass feedstock production. (2) Determine the agronomic potential of intersowing of winter camelina as a cover crop into a standing soybean or maize crops in order to increase soil cover in late fall and early spring, scavenge nutrients and provide nutrients for the following cash crop. (3) Determine the environmental impact of cropping systems involving late-season and intersown cover crops, intercropping, and to compare with cropping systems common to the region, using LCA and impact analysis.

CHAPTER 2. GENERAL LITERATURE REVIEW

2.1. Rising Demand for Food In The Future

The demand for food will continue to increase as a result of population growth. The human population has nearly quadrupled in the past 100 years, and it is estimated to increase from 6.7 billion in the year 2006 to 9.2 billion by 2050 (UNFPA, 2007). It took only 12 years for the last billion to be added in to the world's population with an increase of nearly 230 000 humans per day. Additionally to the rising population, dietary changes also have affected the world food consumption, due to the increased wealth, and higher purchasing power of a large fraction of the world's population. This has resulted in increased consumption of food per capita, and the demand of high protein food such as meat, dairy, and fish (Keyzer et al., 2005). By 2030, demand for food and meat will increase by 50% and 85%, respectively (Evans, 2009). It is estimated that per capita meat consumption will increase from 37 to 52 kg per person per year, between the year 2000 and 2050 (FAO, 2006). The demand for cereals, including wheat, rice (*Oryza sativa* L.), and maize accounts for about 50% of the human calorie intake (Nellemann et al., 2009). Nearly half of the cereal produced in the world, is used for animal feed (Keyzer et al., 2005). During the past 50 years, global numbers of cattle, sheep (*Ovis aries* L.), and goat (*Capra hircus* L.) had a 1.5-fold increase, while swine (*Sus scrofa* L.), and poultry numbers increased by 2.5- and 4.5-fold, respectively (FAO, 2009).

World food production went through a significant growth during the past half-century due to factors such as; use of improved germplasm, chemical fertilizers, chemicals to protect crops from pests and weeds, improved irrigation systems, and the expansion of agriculture into new lands (Evans 2009; Godfray et al., 2010; Gregory and George 2011). As a result, the proportion of the population undernourished decreased, despite an increase in population (World

Development Report, 2008). However, one in seven people today still do not have access to sufficient protein and energy from their diet, and even more suffer from some form of micronutrient deficiencies (FAO, 2009).

Until recent, there was a widespread assumption that food security depended on food distribution and access, not food production (Gregory and George, 2011). In 2008, a world food crisis was a result of a combination of factors, such as; competition for cropland for biofuels production, low cereal stocks, high oil prices, speculation in food markets, and extreme weather events (Nellemann et al., 2009). The crisis led to the dramatic increase in several commodity prices, drove 110 million people into poverty and added 44 million more to the already undernourished population (World Development Report, 2008).

Therefore, today's world challenge resides in matching the rapid demand for food from a larger and more wealthy population while protecting the environment and ensuring that the world's poorest people have sufficient access to food (Braun, 2007). This challenge requires changes in the way food is produced, stored, processed, distributed, and, accessed (Godfray et al., 2010).

2.2. Challenges Faced When Increasing Food Production

Currently, food production is faced with several challenges such as; greater competition for land, water, and energy, and the need to reduce negative impacts on the environment (Tilmen et al., 2002; Millenium Ecosystem Assessment, 2005; Schmidhuber and Tubiello, 2007). Competition for land is likely to become a major problem for food production in the future. From the 13.4 billion ha of land in the world, about 3 billion ha is considered suitable for crop production, and nearly half of this is already cultivated (Smith et al., 2010). Furthermore, the demand for land from other uses such as biofuels, timber, carbon sequestration, forest conservation, and urban and infrastructure development is intensifying with the growing population (Evans, 2009).

Production of other non-food crops is also projected to increase. Ethridge et al. (2006), stated cotton (*Gossypium hirsutum* L.) production is expected to increase to an additional 2% of cropland area by 2030 and 3% by 2050. Demand for biofuel also has increased crop land use (FAO, 2008). In 2004, 14 million ha of crop land worldwide was used for energy crops production which accounts for 1% of the total cropped area (IEA, 2006). Growing crops for biofuels have increased, responding to a need for energy security, transportation fuels, and decreased GHG gases emissions (Gregory and George, 2011). But for many developing countries, such as Brazil, Indonesia, and Malaysia, biofuels are considered as an opportunity to improve rural livelihoods and the economy (Fitzherbert et al., 2008). Even though biofuels are a potential low carbon energy source, the conversion of rainforests, savannas, or grasslands to produce biofuels in the USA, Brazil, and Southeast Asia actually can release 17 to 420 times more CO_2 than the GHG reduction by displacing fossil fuels (Fargione et al., 2008; Searchinger et al., 2008).

Infrastructure and urban development is increasing rapidly to accommodate the growing population (UN, 2008). Since people historically settled in the most productive locations, cropland adjacent to towns and cities has been used to accommodate urban infrastructure such as roads and housing. Additionally, in recent past, productive agricultural land has been lost to desertification, salinization, soil erosion, and other consequences of unsustainable land management (Nellemann et al., 2009). It is estimated that between 2 000 000 and 5 000 000 ha of land are affected annually by land degradation, mainly soil erosion, with most losses in Africa, Latin America, and Asia (Den-Biggelaar et al., 2004). As a result of intense competition for suitable crop land, and due to the degradation of existing crop land, per capita arable land area will continue to decrease. It decreased from 0.415 ha in 1961 to 0.214 ha in 2007. Future increases in crop production will be from the higher cropping intensity (Smith et al., 2010).

Water scarcity is already becoming a major problem as population grows and per capita consumption rises. About half a billion people live in countries chronically short of water; by 2050, the number will rise to more than four billion (Evans, 2009). Water will be the most important factor affecting future food production, because of climate change, and also as a result of unsustainable extraction from rivers, lakes, and groundwater (FAO, 2009). Agriculture, accounts for 70% of global fresh water use. Irrigated land currently produces 40% of the world's food on 17% of its land (FAO, 1999). Supply of water for agriculture is highly dependent on natural ecosystems and natural vegetation such as forests in terms of flow regulation (Nellemann et al., 2009). This is critical for to provide a dependable water supply to crop land, by retention of water in wetlands and forests, and buffering both droughts and floods (Bruijnzeel, 2004).

Currently, food production is dependent on high yields from intensively managed crop systems (Robertson et al., 2014). However, more diverse crop rotations using fewer inputs can provide similar or greater yields than those of conventional crop rotations (Drinkwater et al., 1998). In the US Midwest, 60% of maize production area is in rotation with soybean and 25% in continuous maize (Osteen et al., 2012). Less diverse crop rotations are a result of: 1) highly mechanized agriculture, 2) US government farm subsidies, 3) 2007 US legislative mandate to blend maize-based grain ethanol into gasoline, 4) incentives to increase maize presence in crop rotations, and 5) crop insurance subsidies that reduce farmer incentives to manage risk through crop diversity (Robertson et al., 2014). In 2011, 94% and 70% of US soybean and maize production areas were planted with herbicide-resistant cultivars (Osteen et al., 2012), respectively. Reduced plant diversity can have negative effects on many taxa such as arthropods, vertebrates, microbes, and other soil organisms. The loss of these taxa can have negative effects on community structure and dynamics such as species extinctions and changes in trophic structure (Zhang et al., 2007). Continuous monocultures yield decreases overtime even with increased external inputs. Yield reduction overtime is attributed mainly to the loss of beneficial soil microbes and macrofauna (Zhang et al., 2007; Bennett et al., 2012). High input agriculture also has led to negative environmental impact either on- or off-site. High fertilizers use has led to land, water, and air degradation by leaching, eutrophication, and GHG emissions (Vitousek et al., 2009). Ideally, fertilizers and soil biota should be managed to deliver nutrients to crops synchronously with demand, but unfortunately, most fertilizer applications are done before crop demand, increasing the risk of leaching and run-off (Gregory and George, 2011).

2.3. Cropping Systems

In order to face the challenge of feeding increasing world population and to fulfill other land use needs, the productivity and labor utilization per unit area of currently available land needs to be increased (Heaton et al., 2013). Several sustainable intensification strategies can be used to improve land productivity. Conventional intensification usually is achieved by advanced genetics and technology, increased inputs and infrastructure targeting yield-limiting traits. Temporal intensification is defined as increasing the number of crops grown in a given period of time. Using more of the growing season by including cover crops, double- and relay-crops, and intercrops (Heaton et al., 2013) or intensifying cropping systems by conventional or temporal intensification or a combination of both can improve land productivity while improving sustainability of current cropping systems. A cropping system is the combination of crops grown on a given area within a given time period (Seran and Brintha, 2010). Throughout the world, different cropping systems can be found depending on the local climate, soil characterristics, economic factors, and social aspects (Seran and Brintha, 2010).

2.3.1. Common Crop Rotations in the Northern Great Plains Region

The northern Great Plains of the USA comprises mainly of the states of North Dakota, Minnesota, South Dakota and northern Iowa, and considered the most important food crops producing area in the USA. The NGP consist of a semi-arid, and prairie landscape with an extensive area of rainfed crop production. Most soils in the NGP were formed by loosely compacted parent materials, with textures of silt loam, silty clay, and loamy sands (Stewart et al., 2010). The climate is characterized by hot summer days with high sunlight intensity, a summer rainfall pattern, and cold, dry winters (Farahani et al., 1998). Hansen et al. (2012) indicated that the high level of temporal and spatial climate variability is a major challenge to dryland cropping in this area where periods of severe drought or short-term drought within a growing season are common.

The NGP agriculture used to be dominated by perennial grasses and legumes used for forage production and grazing until the late 90's (Hudson, 2011). In 1999, the NGP had more than 11 million ha dedicated to forage production (NASS, 1999). Forage production in the NGP involves cultivated and native pasture and hay production. The states of North Dakota, South Dakota, and Minnesota produced 1 880 000 ha of alfalfa (*Medicago sativa* L.) and alfalfa-grass mixtures in 2014 generating more than $1.27 billion to the US economy. Maize silage was produced in over 376 300 ha in 2015, in the above mention three states (NASS, 2015).

Crops such as wheat, soybean, maize, canola (*Brassica napus* L.) and other cool-season cereals are common in crop rotations in the NGP, with wheat and canola distributed mainly in the northwestern tier of the NGP and maize and soybean in the southeastern part (Hudson, 2011).

Maize and soybean acreages have been expanding North and West in the Corn Belt region due to a longer season, warmer temperatures (Wolfram and Michael, 2009), higher prices between 2009 and 2013, and the development of new early-maturing cultivars adapted to grow in northern areas (Weise, 2013). Currently, the most common cropping system in the southeastern part of the NGP is soybean-maize (NASS, 2014). Higher commodity prices from 2009 to 2013 led farmers to turn marginal and conservation reserve program (CRP) land into annual cropping systems with detrimental consequences to wildlife, water quality, and global warming (Langpap and Wu, 2011). The transition of CRP and perennial grasslands into annual crops is impacting negatively towards ecosystem services such as; pest suppression, pollination, and conservation of wildlife (Werling et al., 2014). Conventional crop intensification has caused a dramatic reduction in crop diversity and other negative environmental impacts such as nutrient leaching and run-off and soil erosion (Robertson et al., 2014).

2.3.2. Intercropping

Intercropping can be described as, the growing two or more crops simultaneously on a single field for all or part of their growth cycle in a season (Gallagher, 2009; Machado, 2009). Before the green revolution, intercropping was a common practice in the USA and Europe (Kass, 1978). After the green revolution, with increased mechanization in agriculture along with the availability of relatively cheap synthetic agrochemicals and fertilizers, crop production moved away from intercropping and leaned toward short-rotations or monoculture (Horwith, 1985). With increasing fertilizer costs, along with the various environmental concerns associated with synthetic fertilizer usage such as global warming, and eutrophication, the relevance of intercropping is being revisited (Machado, 2009; Borghi et al., 2013).

Increased crop diversity can improve overall yield stability, thus the resilience of the cropping system, especially when faced with adverse weather conditions such as droughts (Gaudin et al., 2015). Interaction among plant species can include both negative and positive aspects. Understanding these interactions will be essential to manipulate factors in order to get the maximum benefits from an intercropping system. Heaton et al. (2013), described intercropping practices depending on the temporal and spatial distribution of the crops involved. Gallagher (2009) and Lithourgdis et al. (2011) defined several terms such as mixed intercropping, row intercropping, within-row intercropping, and strip intercropping. Mixed intercropping is where two or more crop species are grown without any distinct arrangements of rows. In row intercropping different crop species are cultivated in separate alternate rows. If different crops were planted within the same row it is described as within-row intercropping. In strip intercropping, several rows of a specific crop are alternated with several rows of another crop species. Relay cropping is defined as, two crops which growth cycles overlap at the beginning or end of the season (Gesch and Archer, 2013). Relay cropping systems where the second crop is seeded into a living first crop could have an interesting niche in NGP region. Winter camelina, an industrial oilseed, has been identified as an excellent crop for relay-cropping in the North Central USA (Gesch et al., 2014). Winter camelina is known for its winter hardiness and can be planted in the fall maturing early in the following summer, allowing a second crop to grow and produce accaptable yields (Gesch and Archer, 2013, Gesch et al., 2014; Berti et al., 2015). The choice of crops and their response in intercropping system will depend on several factors such as time of planting, crop maturity, planting density and pattern, fertilizer application, and pest and weed management (Fukai and Trenbath, 1993; Seran and Brintha, 2010;).

Efficient resource utilization is considered to be the main advantage of intercropping (Seran and Brintha, 2010). The use of resources will depend, on the individual crops and on complementary effects between crops in the cropping system (Seran and Brintha, 2010). Difference in rooting structures and leaf arrangement in different crops will result in efficient harnessing of light and water, compared with a monoculture. Blade et al. (1997) stated, partitioning of limiting resource among crops can be observed when they are grown in association.

Land equivalent ratio (LER), is commonly used to measure the land productivity and efficiency of an intercropping system. Ning et al. (2012), defines LER as the relative land area needed for a monocrop to produce the same yield obtained with intercropping. If the value of LER is greater than one, intercropping yield is higher than that of the monocrop (Hamzei and Seyedi, 2015). In a study done in the North East USA, Bybee-Finley et al. (2016) reported LER values of 2.0 and 3.65 for intercrops containing sorghum, thus indicating the improved efficiency of intercropping, compared with that of monocrop.

Intercropping has the potential to improve the diversity, stability and resilience of the system compared with monocultures grown on the same area (Anil et al., 1998; Lin, 2011; Gaudin et al., 2015). Agroecosystem stability refers to cropping systems ability to maintain yields after a stress period and includes various concepts such as resilience, persistence, and resistance (Harrison, 1979). Resilience is defined as the ability of a system to return to its original state following a perturbation (Holling, 1973). However, stability and resilience are often used interchangeably to describe fluctuations in final crop yields (Gaudin et al., 2015). Cropping systems are considered stable or resilient, if they retain yield potential and recover functional integrity (produce food and feed) when challenged by environmental stresses (Lin, 2011; Gaudin et al., 2015).

Intercropping systems can provide more competition against weeds either in time or space than a monocrop (Seran and Brintha, 2010). Dimitrios et al., 2010 reported weed density decreased in a maize-legume intercrop compared with a monocrop, due to the reduction of available photosynthetically active radiation light under the canopy of maize plants and legumes, compared to that of maize in monoculture. A second crop in an intercropping system can act as a barrier against the spread of pests and diseases. Henrik and Peeter (1997), reported reductions in stem borer (*Papaipema nebris* Guenee) damage in maize when intercropped with cowpea [*Vigna unguiculata* (L.) Walp.]. Intercropping can prevent soil erosion by minimizing rain water drops hitting the soil directly (Seran and Brintha, 2010), by covering the soil thus preventing surface exposure to water (Kariaga, 2004), or acting as wind-barrier to prevent wind erosion and excessive soil water evaporation (Prashaanth et al., 2009).

2.3.3. Potential of Forage Sorghum in Intercropping Systems for Silage and Biogas Production

Forage sorghum is used as single-cut hay, direct grazing, but mainly as silage (Undersander et al., 2010), but Berti et al. (2015), suggested forage sorghum can be used in intercropping, double- and relay-cropping systems, and also as a cover crop. Forage sorghum is known to be drought tolerant, where it uses about 350 mm per year (Undersander et al., 2010), in contrast to higher water use in maize with 500 to 890 mm per year (Frankenfield, 2014). Maize biomass yield between 27 and 32 Mg ha^{-1} under irrigation was reported by Bean and Marsalis (2012), while forage sorghum yield ranged between 16 and 28 Mg ha^{-1} (Rooney et al., 2007; Samarappuli et al., 2014). Forage sorghum and maize produce similar biomass yield per unit area (McCollum et al. 2005; Rooney et al., 2007). However, sorghum has a lower digestibility and higher fiber content, compared with maize silage (Undersander et al., 2010). But, when compared with maize, forage sorghum has several advantages to compensate its lower feed quality, such as higher water use efficiency (McCollum et al., 2005), ability to tolerate heat and drought stress (Rooney et al., 2007), efficient in utilizing P and K (Shoemaker and Bransby, 2011), and has a lower seeding costs (Bean and Marsalis, 2012).

Significant genetic improvements in forage sorghum have resulted in the development of high yielding forage cultivars with increased forage digestibility, improved tolerance to stresses such as diseases, and drought (Rooney et al., 2007). One such discovery is the brown midrib (BMR) character in sorghum and maize. This character indicates lower lignin content in the plant. The BMR-sorghum cultivars have 25 to 50% less lignin (Dien et al., 2009), greatly improving forage digestibility and palatability (Bean and Marsalis, 2012). Many of the BMR sorghum types are associated with lower dry matter yield, plant height, and tillering ability compared with non-BMR types (Shoemaker and Bransby, 2011). As a result, there are new efforts to develop BMR-sorghum cultivars which are higher in leaf to stem ratio to offset any yield loss.

European countries such as Germany, Austria and Italy, where production of bioenergy from biogas is a main focus. This is due to growing energy need, diminishing supplies of fossil fuels, and climate change concerns (Oslaj et al., 2010). Biogas, composed mainly of CH_4 and CO_2, is obtained by anaerobic digestion of organic matter, which can then be converted into electricity (Weiland, 2010). The production of biogas under anaerobic conditions offers many advantages over fossil fuel, such the reduction in GHG emissions and increase on production of co-products, such as organic fertilizer which can substitute for synthetic fertilizer (Fehrenbach et al., 2008).

Biogas production from agricultural biomass also offers significant environmental benefits and serves as an additional source of income for farmers (Oslaj et al., 2010). With biogas production, the key factor to be considered is the methane yield per unit area of land. This may be influenced by harvesting strategies, processing technologies, crop species used, genotypic variations in crops, composition and biodegradability of biomass (Mahmood et al., 2013). Maize silage is considered a key substrate for agricultural biogas production due to its high biomass yield and high content of water-soluble carbohydrates and proteins, as well as their structural carbohydrates; cellulose and hemi-cellulose (Oslaj et al., 2010, Mahmood et al., 2013).

However, due to concerns over diversity in crop rotations and soil conservation, and with the increase of maize pests, in 2012, the maximum input of maize silage as substrate for biogas plants was limited to 60% dry mass fraction in Germany (Windpassinger et al., 2015). As a substitute for maize, forage sorghum recently has gained attention as a novel feedstock crop (Negri et al., 2014; Windpassinger et al., 2015). Therefore, intercropping maize with forage sorghum would establish a system that can combine the advantages of both crops and also would improve the resilience of the system and would not require of as many inputs as maize monocrops.

2.3.4. Double Cropping

Double-cropping can be defined as growing two crops in succession, in the same field, during the same growing season where the second crop is seeded after the harvesting of the first crop (Hexen and Boxley, 1986; Kyei-Boahen and Zhang, 2006). This temporal diversification usually is intended to increase the land use efficiency and yield per unit of cropping area, while enhancing profits (Heaton et al., 2013; Gesch et al., 2014). Double-cropping systems have the potential to increase annual dry matter production per season (Goff et al., 2010), return more organic residues to the soil, compared with a single crop to improve soil structure (Murdock et al., 1997), prevent soil erosion (Krueger et al., 2012), reduce N leaching and runoff (Heggenstaller et al., 2008), weed suppression (Davis, 2010), and provide many other ecosystems services, such as enhance pollinator abundance, alter herbivory efficiency, and increase arthropod biodiversity (Loranger et al., 2013; McArt and Thaler, 2013).

Relatively long growing season and water availability favors double-cropping in the southern and coastal states of the USA, where a winter-cereal followed by soybean is the most common double-crop system (Kyei-Boahen and Zhang, 2006). Double-cropping is limited in northern areas of the USA due to the much shorter growing season, especially when planting the second crop after the first crop is harvested. However, double-cropping has been tested in the Corn Belt region with winter cereals followed with a grain crop and also with a forage/biomass crop (Krueger et al., 2012). Under these conditions, the winter cereal is harvested for forage before physiological maturity to allow sufficient time for the second crop to mature for grain production (Krueger et al., 2012). Heggenstaller et al. (2008) reported an increase of 25% in total dry matter production in double-cropped triticale (x *Triticosecale* Whittman)-maize and triticale-sorghum/sudangrass (*Sorghum bicolor* var. *sudanense* L.) when compared with mono-cropped maize. Due to many benefits in double cropping, Pullins et al (1995), indicated identifying alternative crops adequate for double-cropping that can fit into existing and common cropping systems with little or no added equipment cost, and minimal changes in management are needed.

2.4. Cover Crops

Cover crops can be defined as non-cash crops that are grown with or after a cash crop (Bich et al., 2014). The statistics report from the census of 2012 (NASS, 2014) indicates there are approximately 4 million ha of cover crops planted in USA, which represents 2% of the total annual crops area. In North Dakota and Minnesota, 86 563 and 165 259 ha of cover crops were planted in 2012, respectively. Cover crops have become a viable option for sustainable agriculture because of their contribution to the environment, soil fertility, and improved crop performance (Gaudin et al., 2013; Bich et al., 2014; Ketterings et al., 2015).

The benefits provided by cover crops are dependent on several factors such as; the species involved (Wortman et al., 2012), time of establishment (Bich, 2013), seeding rates (SARE, 2007), environmental conditions (De Haan et al., 1997), crop rotation (MCCC, 2012), and previous herbicide applications (Bich, 2013).

Because of their inherent symbiotic ability, leguminous cover crops can fix atmospheric N_2 and reduce the use of synthetic N fertilizers and production costs. Nitrogen accumulation by leguminous cover crops can range from 60 to 200 kg N ha^{-1} (Samarappuli et al., 2014; Ketterings et al., 2015). The amount of N available from legumes depends on the species, total biomass produced, location, sowing date, content of N in the plant tissue, and tillage used in the following season (Sullivan, 2003; Fageria, 2007; Ketterinngs et al., 2015). Crimson clover (*Trifolium incarnatum* L.), hairy vetch (*Vicia villosa* Roth.) and pea (*Pisum sativum* L.) are the most popular legume cover crops in the United States (Groff, 2015) Furthermore, biomass of legumes is considered to be easily degradable in comparison with other crops such as grasses (Mihailovic et al., 2006), releasing higher amounts of nutrients for subsequent crops. Inclusion of legume cover crops in rotations may also increase aggregate stability through greater polysaccharide production by microbial communities (Haynes and Beare, 1997).

Non-leguminous cover crops in the Brassicaceae family are known for their potential to scavenge excess N and other nutrients from deep in the soil thus minimizing nitrate losses. These cover crops occupy the fields before and after a regular cash crop, thus more nitrates can be scavenged from the soil profile and cycled by plants and soil microbes (McSwiney et al., 2010). The N uptake by a non-legume cover crop after the harvest of a cash crop, averages between 20 and 60 kg N ha^{-1} and a winter cover crop can reduce N leaching up to 70% compared with a no cover crop (Tonitto et al., 2006).

Cover crops also provide a range of additional benefits to a cropping system. An increase in soil organic matter improves the population of soil microbes and earthworms, which in turn contribute to efficient nutrient cycling through partial digestion and breaking up of soil organic matter (Zhang et al., 2007). Soil organic matter content influences soil compactability, water holding capacity, and soil permeability (Carter, 2002). Deep-rooted cover crops help alleviate soil compaction, which improves water infiltration (Williams and Weil, 2004; Newman et al., 2007). Some cover crops species have been shown to be an effective means of suppressing weeds due to their rapid growth and leaf canopy closure (Fisk et al., 2001; Brust et al., 2014). Some members of the Brassicaceae family can release compounds toxic to plants, fungi, nematodes, and certain insects when incorporated into the soil (Haramoto and Gallandt, 2005). In addition, some cover crops improve P availability and uptake (Sundermeier, 2008). This can be by mineralization of unavailable native P, and unutilized fertilizer-derived P (Cavigelli and Thien, 2003). This will enable the subsequent crop to utilize the readily available P for growth and development. Cover crops residue can release H_2CO_3 during decomposition (Sharpley and Smith, 1989) acidifying the soil, increasing P solubility and availability for plants (Hargrove, 1986).

2.4.1. Late-Season Cover Crops

Harvesting and baling maize stover from fields in the NGP has increased (Bich et al., 2014), and the interest of growing a cover crop in the fall in these fields has increased significantly (Mamani-Pati et al., 2010). Late-season cover crops can reduce N leaching losses. The amount of residual N taken up by cover crops will depend on the cover crop species, sowing date, fall and spring weather patterns, crop growth, and tillage (Snapp et al., 2005). Late-season cover crops can reduce N leaching by reducing the depth of nitrate movement and retaining it in the root zone for uptake (Ketterings et al., 2015). In the dryland areas of the U.S. western Corn Belt, sowing a cover crop in maize production systems is done after fall harvest, but it is challenging due to narrow establishment window, shorter growth period, and limited soil water availability (Bich et al., 2014). Cover crops can be seeded by drilling or broadcasting. Drilling will ensure a good seed-to-soil contact thus triggering germination, given that soil moisture is available. Commonly, drilling is delayed until the harvesting of the cash crop. Aerial broadcasting can be done into a standing cash crop before harvesting, which allows early seeding of the cover crop, but this method is reported to have a lower establishment efficiency compared with drilling (Kladivko, 2011; Salon, 2012). Aerial seeding limitations include the dependence on rainfall right after the crop is seeded. Furthermore, large seeded crops such as peas do not establish well with aerial seeding (Dr. M. Berti, personal communication, 2015).

As a result, the practice of intersowing a cover crop into a standing cash crop has been gaining interest (Roth et al., 2015). In 2015, 4000 ha of cover crops were intersown into maize in the US North East (Groff, 2015). Cover crops can be sown in the V4 to V6 stage of maize (Roth et al., 2015). Drilling is a better practice than broadcasting since previous crop residue does not allow seed to soil contact increasing the risk of stand failure (Roth and Curran, 2014; Groff, 2015;). Caution must be taken not to sow a cover crop too early during the cash crop’s critical weed-free period, to avoid competition (Bich et al., 2014). The critical weed-free period for maize is considered to be from the VE to V8 stages (Moriles et al., 2012). Annual snail medic

(*Medicago scutellata* (L.) Mill.) broadcasted immediately after maize seeding produced biomass yields of 603 and 913 kg ha^{-1} without N and with 120 kg N ha^{-1}, respectively. However this contributed to yield losses between 8 and 23% when compared with maize grown alone. Losses were likely due to competition for N and water (Smeltekop et al., 2002).

In an ideal situation, intersowing a cover crop into a standing cash crop allows the cover crop to germinate and establish after the cash crop's critical weed-free period, but before the likely dry fall conditions. Since the cover crop is sown later and will grow very slow under the crop canopy, nutrients and water uptake is likely to be minimal (Groff, 2015). Once the cash crop begins to dry and shed leaves, the cover crop resumes growth. By harvest, the cover crop is actively growing and upon receiving favorable environmental conditions will establish and grow rapidly (Hartwig and Ammon, 2002; Bich et al., 2014; Groff, 2015).

Cereal rye is considered the most popular cover crop in the northern US due to its winter hardiness, late-season growth, and spring growth (Dabney et al., 2001; Groff, 2015). A survey of New York dairy farmers, revealed that of the 88% of them added a late-season cover crop to their silage maize rotation, 63% planted cereal rye (Long et al., 2014). Nitrogen uptake of cereal rye seeded in late August to early September after maize, was 32 kg N ha^{-1} on average (Ort et al., 2013). Nitrogen accumulation of cereal rye, when seeded as late-season cover crop depends on fall seeding date and spring termination date. Highest N accumulation rates of 50 kg N ha^{-1} were reported with early fall seeding (late-August) and late spring termination (mid-April) dates (Ort et al., 2014; Ketterings et al., 2015). Furthermore, cereal rye can reduce soil erosion when planted as a late-season cover crop (Groff, 2015).

However, many maize growers are reluctant to use cereal rye as a late-season cover crop due to the perceived potential for cash crop yield reduction after termination of the cereal rye stand. Early-season N release from late-season cover crop residue depends on microbial mineralization of C and N (Andraski and Bundy, 2005). Mineralization rate is influenced by the C:N ratio of the residue, its quantity and degree of incorporation in the soil, and soil temperature and soil water content (Ketterings et al., 2015). Depending on the soil conditions and method of residue incorporation, N release can take up to three weeks after incorporation (Duiker and Curran, 2005). Additionally, maize biomass yield decreased 11 to 17% when planted soon after a cereal rye cover, likely as a result of phytotoxic compounds exuded by the roots (Raimbault and Tollenaar, 1990). Termination of cereal rye is recommended three weeks prior to maize planting to overcome any allelopathic effects.

2.4.2. Winter Camelina as a Late-Season Cover Crop

Winter camelina is a promising winter-hardy cover crop for maize soybean based-systems. Camelina has been evaluated mainly as an oilseed crop but its development as a cover crop is recent. Camelina belongs to the family *Brassicaceae*, and is commonly known as ‘Gold of Pleasure’ or false flax (Grady and Nleya, 2010). It is native from Finland to Romania and found east of the Ural Mountains (Ehrensing and Guy, 2008). Camelina seed oil content ranges between 30 to 40% and can be used for edible and industrial products (Grady and Nleya, 2010).

Camelina is a short-season crop, reaching maturity at 85 to 100 days after seeding in the spring. Plants can reach 30- to 90-cm in height (Grady and Nleya, 2010). Flowers are small, pale to green-yellow in color, and are mostly self-pollinated (Groeneveld and Klein, 2013). Camelina fruits are silicles, more commonly known as pods. Seeds are quite small with a 1000-seed weight between 0.8 to 2 g (Ehrensing and Guy, 2008).

Camelina requires minimal seedbed preparation (Ehrensing and Guy, 2008), although a firm and moist seedbed is preferable (Grady and Nleya, 2010). Research done in USA indicates that 3.4 to 5.6 kg ha^{-1} seeding rate will allow good crop stands (Ehrensing and Guy, 2008; Wysocki and Sirovatka, 2008). Spring and winter types of camelina exist. The most common is spring camelina, which is a spring seeded crop that benefits from early-planting dates and is not winter-hardy (Lafferty et al., 2009). In North Dakota, winter camelina can be seeded during fall (between early-September to mid-October) after a cereal crop harvest. It germinates even when soil temperatures are as low as $1^{o}C$ (Gesch and Cermak, 2011). When fall germination occurs, the plants, still in the rosette stage, stay under the snow cover until temperatures warm up again in the spring resuming growth, followed by stem elongation and branching (Grady and Nleya, 2010). Winter camelina flowers between late April and early June, and could considered as a source of nectar and pollen to both native insects emerging out from winter hibernation, and to honey bee (*Apis mellifera* L.) hives returning in the summer (Eberle et al., 2015), before being terminated or harvested to plant a cash crop. Camelina's ability provide a food source before most crops in the Midwest begin to flower (Eberle et al., 2015; Berti et al., 2016), can also be considered as an important ecosystem service.

Both winter and spring camelina can also be considered as a source of nectar and pollen for honey bees and other pollinators early in the season, before most crops in the Midwest begin to flower (Eberle et al., 2015; Berti et al., 2016), thus providing an important ecosystem service.

Recent findings indicate that camelina when grown as a winter crop may mature early enough to allow double-cropping with a food or forage crop (Berti et al., 2015; Gesch and Johnson, 2015) and has the potential to be used as a cover crop (Berti et al., 2015). According to Berti et al. (2016), camelina has the ability to adapt and grow in different environments in USA and Canada. This resilience can be attributed to its ability to extract water from deep soil layers (Hunsaker et al., 2011). Even though the root development of camelina has not been studied extensively, Gesch and Johnson (2015) reported that more than 80% of winter camelina roots were distributed in the top 0.3-m of the soil. Camelina's tap root system may also enhance nutrient scavenging while the canopy cover will reduce nutrient run-off. Similarly, other tap-rooted brassicas such as radish (*Raphanus sativus* L.) and turnip (*Brassica rapa* L. *var. rapa*) are known for reducing soil compaction, improving infiltration (Dean and Weil, 2009; White and Weil, 2011; Lounsbury and Weil, 2015). Characteristics that are also likely to be provided by camelina.

2.5. Ecosystem Services

In 1992, De Groot defined ecosystem services (ES) as "capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly". Agriculture both depends on, and also, provides ES (Schipanski et al., 2014). Ecosystem services are classified as provisioning, regulating, supporting, or cultural services (Millennium Ecosystem Assessment, 2005; Kragt and Robertson, 2014). Agricultural ecosystems are managed to optimize the provisioning of food, fiber, and fuel, and depend upon a wide variety of supporting and regulating services, such as soil fertility, nutrient and water cycling, soil carbon storage, water and air quality, pest regulation, and supporting biodiversity and pollination. Agriculture also provides cultural services such as recreation and esthetic value (Zhang et al., 2007; Power, 2010; Schipanski et al., 2014). Agriculture also receives several types of ecosystem disservices (EDS) that can reduce yield, quality or increase production costs (e.g., herbivory and competition for water, nutrients, and sunlight) (Schipanski et al., 2014).

These ES and EDS depend on how agricultural ecosystems are managed at the site, and on the diversity, composition, and functioning of the surrounding landscape. Landscapes that contain diverse habitat types typically are more compatible for beneficial insects and most often resulting in improved biological control of pests. Ecosystem services and dis-services are influenced both by the location and type of farming (Zhang et al., 2007). All major cereal grain producing regions of the world such as the North American prairie, the Asian steppe, and the South American pampas have common characteristics such as topsoil rich with organic matter and good soil water holding capacity (Zhang et al., 2007). Ecosystem services to agriculture also affect farmland's economic value. The value of agricultural land depends on production costs linked to ES such as soil fertility, suitable climate and lower pest pressure (Roka and Palmquist, 1997).

Increasing the diversity in the cropping systems by incorporating cover crops, intercropping, employing perennial grassland in the marginal land areas, switching from annual to perennial systems enhances many ES. A three-year, six-species rotation of maize, soybean, and wheat, with three cover crops to provide N, in southwest Michigan, produced maize yields comparable to county average, in addition to rotational benefits and other ecosystem services (Smith et al., 2008). Using cover crops into a three-year soybean-wheat-maize cropping system increased eight out of eleven ecosystem services studied, without decreasing productivity (Schipanski et al., 2014). Improving agroecosystem diversity can improve the cropping systems resiliency to weather shocks increasing the probability of obtaining high maize yields while decreasing vulnerability of maize and soybean yield to weather variations (Gaudin et al., 2015). Most of the ES and the functions that supply them are context-dependent (Kremen, 2005), therefore a universal indicator on what is considered as an ES, rarely exist (Zhang et al., 2007). Management decisions of ES within agricultural systems will typically involve trade-offs, some of them among different services (Millennium Ecosystem Assessment, 2005). Due to trade-offs and interactions among ES, it is challenging to manage agricultural systems to optimize economic returns while improving multiple ES simultaneously (Power, 2010). There can be direct trade-offs such as, increased use of fertilizer helps maximize crop yields, but can result in water quality degradation (Jaynes et al., 2001). There are also trade-offs, that are indirect, such as improving plant diversity which may increase biological control of pests, but also it could increase competition with crops leading to a penalty in biomass production (Zavaleta et al., 2010). Furthermore, temporal scales also contribute to indirect trade-offs. Management practices aimed at maximizing current crop production may degrades soil quality over time (Rodriguez et al., 2006). The widely understood approach to address these situations is to recognize that agriculture can provide ecosystem services other than grain or yield (Zhang et al., 2007; Robertson et al., 2014).

Since most cropping systems are valued in terms of grain yield and short-term profitability and if measured in terms of ES offered, current cropping systems may not be providing many benefits to the environment (Schipanski et al., 2014). Several recent studies in cropping systems in the Midwest and eastern US suggest that cropping systems focused on grain yield and profit, may be neglecting ecosystem services (Schipanski et al., 2014; Syswerda and Robertson, 2014; Werling et al., 2014). North Dakota is ranked number one in the US for at least 12 food crops, including most cool-season cereals, oilseeds, grain legumes or pulses, and also honey (NASS, 2015). The ecosystems services provided by most of these annual crops are limited. Also, the growers have the perception that any increase in variation in management practices intended to increase biodiversity or ecosystem services will hinder productivity and their short-term profit (Robertson et al., 2014). Annual cropping systems can provide five major ecosystem services: food and fuel, pest control, clean water, climate stabilization through GHG gases mitigation, and soil fertility.

2.5.1. Providing Pest Protection through Biocontrol

Biodiversity at the landscape scale also affects the capacity of agriculture to deliver ecosystem services, such as biocontrol. Ladybird beetles (Order: Coleoptera, Family: Coccinellidae) are important predators of aphids in field crops such as soybeans (Robertson et al., 2014). Ladybird beetles are responsible for soybean aphid (*Aphis glycines* Matsumura) control and are able to keep aphid populations below economic thresholds (Costamagna and Landis, 2006). In the absence of such control, soybean yields can be reduced by 40% to 60% (Robertson et al., 2014). The value of biocontrol in Michigan and three adjacent states was estimated in $239 million in 2007 on the basis of a $33 ha^{-1} increase in profitability in soybean from higher production and lower pesticide costs (Landis et al., 2008). Increased landscape diversity will improve biocontrol efficacy, since different Coccinellidae species require different habitats at different times for food and for overwintering (Robertson et al., 2014).

2.5.2. Maintaining Water Quality

The quality of water draining from agricultural watersheds is a major environmental, concern, because it contains pollutants such as sediment, P, and nitrate (Robertson et al., 2014). Those pollutants can lead to pollution of groundwater, surface freshwaters, and marine ecosystems and create eutrophication, subsequent algal blooms, and finally hypoxic zones (Diaz and Rosenberg, 2008). In the United States, over 70% of the N and P delivered to the Gulf of Mexico by the Mississippi River is derived from agriculture (Alexander et al., 2008).

Management practices such as no-till, other conservation tillage methods and cover crops can help to reduce soil erosion and runoff, thus minimizing sediment and P entering into water bodies (McSwiney et al., 2010). Furthermore, improvements in soil structure in no-till cropping systems allows water to infiltrate quickly, thus reducing equilibration with soil microsites where nitrate is formed (Strudley et al., 2008).

2.5.3. Mitigating Greenhouse Gas Emissions

Agriculture is directly responsible for approximately 10% to14% of total annual global anthropogenic GHG emissions while, this amount consists largely of N_2O emitted from fertilizers and manure, and methane emitted by ruminant animals and burned crop residues (Smith et al., 2007; Kragt and Robertson, 2014). However, GHG emissions related to agricultural land use changes, agronomic inputs, such as fertilizers and pesticides, and postharvest activities, such as food processing, transport, and refrigeration if taken into account GHG emissions increased to up to 36% (Barker et al., 2007). Conventional annual cropping systems had a net annual global warming impact (in CO_2 equivalents [CO_2e]) of 101 g of CO_2e m^{-2}, but the no-till system exhibited net mitigation of -14 g CO_2e m^{-2} (Gelfand and Robertson, 2014). Furthermore, soil carbon storage in the no-till system can contribute to offset the CO_2e of N_2O and fertilizers used in the no-till system (Robertson et al., 2014). In addition, if harvested plant biomass is used to produce energy that would otherwise be provided by burning fossil fuels, the net global warming impact of the whole system will get reduced further as CO_2 emissions from the fossil fuels will be displaced by the biomass-derived energy (Gelfand et al., 2013).

Field management activities have significant impacts on GHG emissions from cropland soils. Studies show N accumulation by leguminous cover crops can range from 60 to 200 kg N ha^{-1} (Hargrove, 1986; Samarappuli et al., 2014; Ketterings et al., 2015) and between 20 and 60 kg N ha^{-1} in a non-legume cover crop (Tonitto et al., 2006). Even though not all the N in a cover crop will get mineralized and available to the subsequent cash crop, N credits will help in reducing N fertilizer rates, thus be an effective pathway to reduce GHG emissions without compromising crop growth and yield.

Abdalla et al. (2014) reported, combining reduced tillage with a mustard (*Brassica juncea* L.) cover crop in spring barley (*Hordeum sativum* L.) in the South East of Ireland had higher N_2O emissions. However, the inclusion of a cover crop increased predicted soil organic carbon, which more than compensated for the higher N_2O flux resulting in a lower total GHG balance compared with the conventional tillage treatment. The authors concluded that the magnitude of compensatory increases in CO_2 uptake by the cover crop contributed to a reduction in the total GHG balance reduction. Bayer et al. (2016) found similar results in a study done in Brazil with no-till, conventional tillage, and cover crops. In this study, no-till soil under legume cover crops was a net sink for GHG.

2.5.4. Improving Soil Structure and Fertility

Soil fertility can be related to different components. Physically, fertility is related to soil structure porosity, aggregate stability, water holding capacity, and erosivity (Zhang et al., 2007). Chemical constituents of soil fertility include soil organic matter, pH, base saturation, cation exchange, and nutrient pools. Microorganisms such as bacteria can enhance N availability through the fixation of N_2 from the atmosphere (Robertson et al., 2014). This occurs most often in legumes that have symbiotic relationships with N_2-fixing bacteria, but free-living soil bacteria can fix N as well (Vitousek et al., 2002). Biologically, soil fertility is related to food web complexity, pest and pathogen suppression, and the delivery of mineralizable nutrients (Robertson et al., 2014). Soil biota helps to enhance soil fertility by extracting nutrients from decaying organic matter and retaining them in their biomass, and also through partial digestion and breaking up of soil organic matter (Zhang et al., 2007). Beetles in the family Scarabaeidae are especially efficient at decomposing wastes generated by large animals, thereby recycling N, enhancing forage palatability, and reducing pest habitat (Losey and Vaughan, 2006).

Certain farming practices, such as mechanical plowing, disking, cultivating, and harvesting can negatively impact or disturb the functioning of soil microbial communities (Zhang et al., 2007) and hinder the buildup of soil organic matter. In a long term study conducted in southwest Michigan by Syswerda et al. (2011) reported, soil organic matter increased in the no-till system compared with the conventional system.

Annual grass species such as cereal rye helps to build water-stable soil aggregates mainly near to the soil surface (Steele et al., 2012). This is mainly due to root secreted polysaccharides which act as a soil binding agent and helps to form aggregates (Liu et al., 2005). Furthermore, Haynes and Beare (1997) reported annual grasses can enhance soil aggregation due to organic matter addition and increased rooting. Legume cover crops such as hairy vetch can reduce soil bulk density near soil surface and increase soil porosity as a result of increased soil organic matter content and root growth (Villamil et al., 2006). Brassica cover crops such as turnip and forage radish have large fleshy tap roots that can grow rapidly, deep in to the soil often through compacted soil layers (Weil et al., 2009; Gruver et al., 2012). When these roots decompose, not only do they add organic matter to the soil but they leave large pores at the soil surface, resulting in increased surface water infiltration and soil air movement (Chen and Weil 2010; White and Weil, 2011).

Cover crops can be used to scavenge excess nutrients remaining in the soil after a cash crop and to supplement nutrient requirements of the subsequent crop (Shipley et al., 1992). Aronsson et al. (2016) reported, cool-season grasses can often be used as “catch crops” to retain excess nutrients. This ability is related to the biomass growth and root development (Thorup-

Kirstensen, 2009). Brassica cover crops are also used to capture nutrients from deeper soil layers due to their rapid growth and deep tap root (Thorup-Kirstensen, 2009). The key to maximize nutrient capture is to establish the cover crop immediately after the harvest of the cash crop to ensure a sufficient growth in the fall and early spring (Komatsuzaki and Wagger, 2015).

2.6. Life Cycle Assessment of Cropping Systems

Life cycle assessment (LCA) is considered as a methodology for compilation and evaluation of potential environmental impacts of a production system throughout its life cycle (Buratti and Fantozzi, 2010). According to the international organization for standardization (ISO), LCA can be used to analyze the life cycle of a particular product, or an activity quantitatively, from production, through use and on to disposal, and recycling, within a generic framework provided by ISO 14040 and ISO 14044 (Singh et al., 2010; Borrion et al., 2012). The evaluation of the life cycle of a product can then be used to compare two different production processes in terms of use of resources and emissions (Petre et al., 2013). At present, LCA is extensively used for evaluating bioenergy and food production systems (Tidaker et al., 2014).

In accordance with the ISO standards, a LCA assessment consists of four major components, namely: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation (Biewinga and Van der Bijl, 1996).

The goal and scope definition provides the basis of any LCA defining the purpose and the extent of the study, and its description (Buratti and Fantozzi, 2010). Goal and scope definition consists of five fundamental steps:

1) Drawing of and initial flowchart for the system to be analyzed. The initial flowchart is the starting point of the study and it shows which processes are involved in the system and their primary or secondary connections (Biewinga and Van der Bijl, 1996; Petre et al., 2013).

2) Choosing a functional unit and reference flow. The functional unit is the unit of measurement to which all the data relate. It allows the comparison among different systems, which are functionally similar, determining energy and mass flows in relation to its value. The functional unit is an important step of any LCA since it provides the reference to which all other data in the assessment are normalized (Bacenetti et al., 2015). In many LCA studies of agricultural production systems, area, such as ha^{-1}, can be considered as the functional unit (Negri et al., 2014). Nevertheless, mass-based indicators such as 1 Mg of dry matter or 1 kg of grain (Bacenetti et al., 2015), and energy based functional units such as GJ ha^{-1} (Monti et al., 2009), can also be considered as functional units (Bacenetti et al., 2015). Due to the multifunctionality of agricultural systems, Nemecek et al. (2011), proposed using three functional units: a) land management function to evaluate the impacts in terms of area and time, b) productive function to analyze the production of food, feed, or biomass and its impact on environment, and c) financial function, since income is the main goal of the grower.

3) Choice of impact assessment method and related impact categories. There are two different types of impact assessment methods: the methods which deal with the impacts caused by the production processes directly to the environment (mid-point methods) and those dealing with the indirect effects to human health, ecosystem health, and resources (end-point methods) (Biewinga and Van der Bijl, 1996). There are a number of impact categories that can be considered in LCA. An impact category exhibits damage to ecological health, human health, or resource availability, while impacts are assessed on global or regional basis (Environmental life cycle assessment, 2014). Most common impact categories are global warming potential (expressed as CO_2-equivalents with a time horizon of 100 years), eutrophication potential (PO_4^{3-} equivalents), acidification potential (as SO_2- equivalents), ozone depletion potential (as CFC

(Chlorofluorocarbon)-11-equivalents), and terrestrial and aquatic toxicity (expressed in kg equivalents of 1-4-dichlorobenzene) (Tidaker et al., 2014; Bacenetti et al., 2015).

4) Definition of system boundaries; system boundaries define the limits of the study stating the processes involved in the system, the time horizon, and the geographical boundaries.

5) Decision on allocation problems; when physical relationship cannot be established as the basis for allocation, the environmental loads such as resource consumption, energy consumption, emissions to air, soil and water etc., should be allocated among the products.

The second phase of a LCA is the inventory analysis. This step includes the construction of the assessment plan according to the system a boundary, the data collection of the input and output flows in each production process, and the calculation of the environmental impacts of the system in relation to the functional unit.

The impact assessment is the third phase of a LCA, which describe the environmental impacts and consequences of the environmental loads quantified in the inventory analysis. The impact assessment is divided in four steps: classification, characterization, normalization, and weighing, as described by the ISO14042 standards. In the life cycle interpretation phase, findings of the LCA are analyzed, make conclusions, and provide recommendations to improve the environmental performances of the system studied according to the ISO14043 guidelines.

In different LCA studies evaluating similar systems, choice of system boundaries and choice of data used in the study varies. Often simplifications are made due to lack of suitable data. Furthermore, capital goods such as machinery and buildings, production and use of pesticides and mineral fertilizers often get excluded from studies involving agricultural products. As a consequence, final results may not be accurate (Roer et al., 2012).

Different LCA studies comparing different cropping systems and final products for food, feed, or energy have yielded a variety of results. Even though energy from lignocellulosic feedstock can be considered a secure, clean, and a low carbon energy source, there can be environmental impacts as a result of feedstock production, harvest and transportation, and energy conversion processes (Borrion et al., 2012). Therefore, the sustainability of the overall system needs assessment and it is a key element in bioenergy production from lignocellulosic feedstock. Using maize ethanol could reduce GHG emissions by 20% instead of using gasoline (Gao et al., 2013). However, if land use change and its impact is included, then maize ethanol would produce 93% more GHG emissions than the production of gasoline. In terms of energy efficiency, maize is better as a food source than bioethanol source (Gelfend et al., 2010). Low input cropping systems are more suited to exploit environmental benefits in biomass production (Goglio et al., 2012). Partially extensive cropping systems including perennial crops for feed which utilize no-till cultivation and reduced mineral fertilizer inputs, resulted in lower environmental impacts in both per unit area and per unit of product, compared with intensified conventional cropping systems (Nemecek et al., 2011). In Italy, in terms of lower land-based impacts, it seems wheat is a better choice than maize to produce first generation bioethanol (Fazio and Monti, 2011).

2.7. Economic Return

Most cropping systems are valued in terms of grain yield and short-term profitability (Schipanski et al., 2014). Economic returns play a critical part in evaluating a cropping system, especially if it is an unconventional and novel system. For an economic analysis, difference in yields, value of the crops, and input costs need to be taken in to account. Adding another crop such as a cover crop, to a conventional monocrop system increases productions costs due to the additional establishment costs, indirect costs associated with management of some cover crops, and opportunity costs of reduced income due to cash crop yield losses incurred from delayed planting, competition, or replacement by cover crops (Snapp et al., 2005).

Most growers are reluctant to change or modify their farming practices unless there are proven benefits associated with the new system. In a survey conducted by Singer et al. (2007), 96% of growers in the US Corn Belt region believed cover crops are effective in reducing soil erosion and 74% recognized cover crops to increase soil organic matter content. Even if growers value such cover crops benefits, some growers consider it is too expensive and they cannot see returns on the investment (Snapp et al., 2005). Therefore, Singer et al. (2007) calculated how much is the minimum payment growers would agree in order to plant cover crops. The mean minimum payment according to this survey was $ 57 ha^{-1} as an incentive to plant cover crops. A dual cropping study done by Gesch et al. (2014) reported that the costs for double and relay cropping camelina in to soybean were higher than that of soybean monocrop. However, inclusion of a legume in to a winter cereal-green manure-maize silage rotation, where the legume was intersown into the cereal, has resulted in a net return of $ 1360 ha^{-1}, reported by Snyder et al. (2016). In addition to direct income, there is a need to value other benefits from a cover crop, such as reducing soil erosion, weed suppression, improving soil organic matter content, and reducing NO_3-N leaching potential (Gesch et al., 2014; Roth et al., 2016; Snyder et al., 2016). Flower et al. (2012) attributed the increased yield in wheat after a cover crop to the increased soil available N and the increased soil water retention provided by the soil cover. However, those authors mentioned the importance of long-term research to evaluate the benefits from a cover crop to a cropping system.

2.8. References

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CHAPTER 3. INTERCROPPING MAIZE AND FORAGE SORGHUM FOR FORAGE BIOMASS, AND BIOGAS, PRODUCTION IN NORTH DAKOTA

3.1. Abstract

Maize (*Zea mays* L.) and forage sorghum (*Sorghum bicolor* L. Moench) are the two most important crops used for silage in the North Central Region. Although most of the silage is for animal feed, there is a potential in utilizing these crops as feedstock for biogas. All maize and sorghum are rain fed crops in this Region, but in some years there is not enough rainfall to have a successful maize crop and most producers do not have irrigation available. As a result, forage sorghum, a more drought tolerant crop, has increased in area. Maize silage is by far the preferred choice for dairy producers due to its high biomass yield and quality, and relative ease of converting to silage. It is also the preferred choice for biogas production. Finding alternative feedstocks for silage and biogas other than maize, is important to have a more resilient production system. Thus, a more resilient system that provides high biomass yield with high dry matter content in a variety of seasonal weather patterns is needed. The objective of this study was to compare different intercropping systems with monocultures and mixed cultures of maize and forage sorghum to determine the most resilient production system in the Region. Experiments were conducted in Carrington, Fargo, and Prosper, ND, in 2013 and in Fargo, ND in 2014. The experimental design was a randomized complete block with three replicates. Experimental units were 9.1 m long and 1.5 m wide with 8 rows spaced 60-cm apart for maize monocrop and intercrop treatments and 31-cm apart for sorghum monocrop treatments. Maize for both silage and grain and two forage sorghum cultivars (Non-Brown Mid Rib (BMR)-S1 and BMR-S2) were grown in monoculture, as well as, both maize cultivars mixed with both forage sorghum cultivars (maize-sorghum). Mixed cultures included row-intercropping and within-row intercropping. The treatments were a total of twelve; 4 monocultures, 4 row-intercropped maize-sorghum, and 4 within-row intercropped maize-sorghum. Crops were harvested the last week of September and samples were collected from each treatment to evaluate biomass yield and quality. Results across locations and years indicated; biomass yield fluctuated between 12.8 to 17.7 Mg ha^{-1} and biogas yield between 12.1 to 16.1 m^3 ha^{-1}. Non BMR forage sorghum (S1) monocultures produced similar or higher biomass yield compared with maize monocultures and maize-forage sorghum mixed cultures (inter-row and within-row). Biogas yield produced by forage sorghum-S1 monocultures, and mixtures containing forage sorghum-S1 were similar to that of grain maize-C1, and silage maize-C2. In conclusion, within-row and inter-row intercropping of forage sorghum-S1 with maize is a promising alternative to maize silage in the North Central region, thus reducing dependence on maize silage production.

Keywords: forage sorghum, resilient production systems, intercropping, mixed cultures, row-intercropping, within-row intercropping, biogas yield

3.2. Introduction

In order to face the challenge of feeding increasing world population and to fulfill other land use needs, the productivity and labor utilization per unit area of currently available land needs to be increased. Improving current cropping systems to intensify the land use will be one such option. Cropping system can be described as the combination of crops grown on a given area within a given time period (Seran and Brintha, 2010). Throughout the world, different copping systems can be found depending on the local climate, soil, and economic and social factors (Seran and Brintha, 2010). Most cropping systems in the Northern Great Plains (NGP) are valued in terms of grain yield and short-term (2-3 years) profitability (Syswerda and Robertson, 2014). The states in the NGP are ranked number one in the U.S. for at least 12 food crops, including most cool-season cereals, oilseeds, grain legumes or pulses, and also honey and livestock. Decreasing crop diversity in the NGP through converting grasslands to monocultures has changed the ability of the environment to provide ecosystem services (Lin et al., 2008).

Intercropping can be described as, the growing of two or more crops simultaneously on a single field for all or part of their growth cycle in a season (Gallagher, 2009; Machado, 2009) Currently, with increasing fertilizer costs and shortages, along with the various environmental concerns associated with synthetic fertilizer usage has brought back the importance of intercropping as part of the solution to these concerns. Intercropping practices depending on the temporal and spatial distribution of the crops involved (Heaton et al., 2013). Mixed intercropping is where two or more crop species are grown without any distinct arrangements of rows. In-row intercropping different crop species are cultivated in separate alternate rows. If different crops were planted within the same row with varying seeding rates, it is described as within-row intercropping. In strip intercropping, several rows of a specific crop are alternated with several rows of another crop species. Relay intercropping is defined as, where the growth cycles of two crops would overlap at the beginning or end of the season (Gesch and Archer, 2013).

Resource utilization is considered to be the main advantage of intercropping. The efficient use of resources will depend, on the inherent ability of individual crops in the cropping system and on complementary effects between crops (Seran and Brintha, 2010). Difference in rooting structures and leaf arrangement in different crops will result in efficient harnessing of light and water, compared with a monoculture. Seed or biomass yield is the primary consideration to assess the potential of a specific intercropping system. It has been shown that intercropping improves the diversity, stability and resilience of the system compared with monocultures grown on the same area (Anil et al., 1998; Lin, 2011; Gaudin et al., 2015).

Intercropping systems can provide more competition against weeds either in time or space than a monocrop and act as a barrier against the spread of pests and diseases, prevent soil erosion, act as wind-barrier to prevent wind erosion and excessive soil water evaporation (Seran and Brintha, 2010). Intercropping can improve the plant nutrient uptake (Li et al., 2003) and a strategy to reduce N leaching (Stoltz and Nadeau, 2014).

Agroecosystem stability refers to cropping systems ability to maintain yields after a stress period and includes various concepts such as resilience, persistence, and resistance (Harrison, 1979). Resilience is defined as the ability of a system to return to its original state following a perturbation (Holling, 1973). Cropping systems are considered stable or resilient if they retain yield potential and recover functional integrity (produce food and feed) when challenged by environmental stresses (Lin, 2011; Gaudin et al., 2015).

Land equivalent ratio (LER), is commonly used to measure the land productivity and efficiency of an intercropping system. Ning et al. (2012), defines LER as the relative land area needed for a monocrop to produce the yield obtained with intercropping. If the value of LER is greater than one, intercropping yield is higher than that of the monocrop (Hamzei and Seyedi, 2015). In a study done in the North East USA, (Bybee-Finley et al., 2016) reported LER values of 2.0 and 3.65 for intercrops containing sorghum.

Forage production in the NGP mainly involves cultivated and native pasture and hay production. In 2014, more than $1.27 billion were generated in the states of North Dakota, South Dakota, and Minnesota by producing 1.88 million ha of alfalfa and alfalfa-grass mixtures (NASS, 2016). Maize silage was produced in over 376 300 ha in 2015, in the above mentioned three states (NASS, 2016).

Resiliency of a forage production system is important in areas where summer rainfall is not sufficient for maize silage production. Maize silage is the most important forage for dairy farms because of the high productivity and forage quality (Coulter, 2008). However, maize requires a more than 350 mm of water and in years with below normal rainfall, maize biomass yields can decrease significantly. Hamilton et al. (2015), reported a yield decrease of 15 Mg ha^{-1} from average yield of 26 Mg ha^{-1}, due to drought, in a study done in southwest Michigan. Forage sorghum is a potential crop to use in intercropping, double- and relay-cropping, and also as a cover crop (Berti et al., 2015). Forage sorghum is used as single-cut hay, direct grazing, but primarily as silage, where rainfall limits maize growth, less than 350 mm per year. (Undersander et al., 2010). In comparison, maize water use lies between 500 to 890 mm per year depending on relative maturity of the hybrid, planting date, weather, and location (Frankenfield, 2014). Forage sorghum produces similar biomass yields per unit area compared with maize, but sorghum contain less amount of grain in the biomass, thus has a lower digestibility and higher fiber content compared with silage maize (Undersander et al., 2010). Forage sorghum silage has lower energy value than maize silage but, both are similar in protein content (Marsalis et al., 2008). However, when compared with maize, forage sorghum has several advantages to compensate for its lower feed quality, such as a higher water use efficiency than maize (McCollum et al., 2005), ability to tolerate heat and drought stress (Rooney et al., 2007), efficient in utilizing P and K (Shoemaker and Bransby, 2011), and lower seeding costs (Bean and Marsalis, 2012). According to previous research conducted in North Dakota, forage sorghum cultivars yields were over 30 Mg ha^{-1} of above ground biomass with sufficient soil moisture, in dryland conditions (Berti et al., 2011). Although is unlikely that dairy farmers will replace maize silage with forage sorghum, there is the alternative of intercropping maize and sorghum to increase system resiliency. A mixed maize-forage sorghum system will have more stable yields in the long-term.

The world today is also faced with problems such as growing energy consumption, diminishing supplies of fossil fuels, and climate change, which has led to research on developing sustainable energy supply systems aimed at covering the energy demand from renewable sources (Oslaj et al., 2010). Biogas from biomass is one such promising renewable energy source whose importance is increasing in Europe (Mahmood et al., 2013a). Biogas production from agricultural biomass also offers significant environmental benefits and serves as an additional source of income for farmers (Oslaj et al., 2010). With biogas production, the key factor to be considered is the methane yield ha^{-1}. This may be influenced by harvesting strategies, processing technologies, crop species used, genotypic variations in crops, composition and biodegradability of biomass (Mahmood et al., 2013a).

The content and availability of feedstock which are able to produce methane is influenced by variety, cultivation and stage of maturity at harvest (Amon et al., 2007). Maize silage is considered as a key substrate for agricultural biogas production due to its high yield potential and chemical composition, including contents of water-soluble carbohydrates and proteins, as well as their structural fibrous ingredients, cellulose, hemi-cellulose, starch and sugar content (Oslaj et al., 2010; Mahmood et al., 2013a).

Many studies have reported that forage sorghum hybrids have potential for increased biomass yields (Rooney et al., 2007; Berti et al., 2011; Samarappuli et al., 2014). Furthermore, sorghum as a bioenergy crop has the ability to be integrated into many production areas and cultivation systems and requires less water, and N fertilizer than maize to obtain a high biomass yield (Rooney et al., 2007; Bean and Marsalis, 2012). Significant improvements in sorghum breeding programs in recent years resulted in the development of high yielding cultivars with increased forage digestibility, improved tolerance to stresses such as diseases, and drought (Rooney et al., 2007). One such discovery is the brown midrib (BMR) character in sorghums. This character is a marker for lower lignin content in the plant. The BMR-sorghum cultivars have 25 to 50% less lignin greatly improving forage digestibility and palatability (Bean and Marsalis, 2012).

Designing an efficient and successful intercropping system needs to consider several factors. The choice of compatible crops and their response in an intercropping system will depend on; time of planting, crop maturity, planting density and pattern, fertilizer application, and pest and weed management. The main objective of this study was to compare different intercropping systems with monocultures and mixed cultures of maize and forage sorghum to determine the most resilient production system in the region.

3.3. Materials and Methods

3.3.1. Field Establishment and Experimental Design

The experiment was conducted at three North Dakota State University research (NDSU) sites at Fargo, (-96° 82’ W, 46° 89’ N, 274 m elevation), Prosper, (-97° 3’W, 46°58’ N, elevation 284 m), and Carrington (-99° 8´ W, 47° 30´ N, elevation 489 m), ND. The soil type in Fargo is a Fargo silty clay soil (fine, montmorillonitic, frigid, Vertic Haplaquoll, with a leached and degraded nitric horizon), while the soil in Prosper has a Kindred- silty clay loam (Perella: fine-silty, mixed, superactive Typic Endoaquoll; Bearden: fine-silty, mixed, superactive, frigid Aeric Calciaquoll), and Carrington has a Heimdahl loam (coarse-loamy, mixed, superactive, Frigid Calcic, Hapludolls) (Web Soil Survey, 2009).

Daily temperature and rainfall were recorded by the North Dakota Agriculture Weather Network (NDAWN) system at all three sites (NDAWN, 2015). Soil samples were taken at all locations for analysis in the spring of 2013 and 2014, before planting. Soil samples were taken at a 0- to 15-cm depth and tested for pH, organic matter, P, and K, while the $N\text{-}NO_3$ analysis was done from the soil samples taken at 0- to 15-cm and 15- to 60-cm in depth (Franzen, 2010). The previous crop was soybean [*Glycine max* (L.) Merr.], at all locations. Chisel plowing was used in the fall after soybean and, in the spring a field cultivator and a roller was used to prepare the seedbed before seeding the experiments.

The experimental design was a randomized complete block with three replicates. Experimental units were 9.1 m long and 2.7 m wide with four rows spaced 61-cm apart for maize, and all intercropping treatments, and eight rows spaced 30-cm apart for sorghum. Two maize cultivars (grain hybrid 75K85 GEN VT2PRO and silage hybrid 2MD95RR) and two forage sorghum cultivars, (non-BMR (brown-mid rib) hybrid 'PampaVerde' and AF-7401; a brachytic dwarf BMR hybrid) were grown in monoculture and as maize-sorghum mixed cultures. Maize seeds were obtained from Peterson Farms Seeds (Harwood, ND), forage sorghum non-BMR hybrid Pampa Verde seeds from Anzu Seeds (Waco, TX), and forage sorghum BMR hybrid AF-7401 from Alta Seeds (Amarillo, TX).

Seeding rates were calculated based on the percentage of pure live seed, taking purity and germination percentage into account. Sowing rates were 29 and 45 kg ha^{-1} for maize and forage sorghum, respectively, targeting plant densities of 86 450 plants ha^{-1} for both monocultures and intercropped crops. There were no additional seed treatments before sowing. Mixed cultures had half of the sowing rate used for the monocultures but targeting the same total plant density of 86 450 plants ha^{-1}. Mixed cultures included row-intercropping and within-row intercropping. Row-intercropping consisted of alternate rows of each crop. Within-row intercropping had both crops (maize and sorghum) mixed before seeding and seeds were placed randomly during seeding (i.e. sorghum-maize seeds were not necessarily alternated within the row). Sowing depth was 50 mm and sowing was done using a 4-cone continuous plot seeder (Wintersteiger, Salt Lake City, UT).

The total number of treatments was twelve; 4 monocultures (grain and silage maize and two sorghum hybrids), 4 row-intercropped maize-sorghum (combination of the same hybrids), and 4 within-row intercropped maize-sorghum Each treatment was assigned to plots randomly and sowing was done in 3 June, 7 June, and 12 June in 2013, in Carrington, Prosper, and Fargo, respectively, and on 4 June in 2014, in Fargo.

All plots were fertilized with 80 kg N ha^{-1} at each location during the second week of July. The source of N was urea [$CO (NH_2)_2$] and each plot was fertilized individually by hand broadcasting. Plots were hand weeded in 2013 and in 2014 the herbicide bromoxynil (2, 6-dibromo-4-cyanophenyl octanoate) + fluroxypyr (1-methylheptyl 4-amino-3,5-dichloro-6-fluoro -2-pyridoxyacetate) at 0.26 kg a.i ha^{-1} was applied.

3.3.2. Sampling and Analysis

When the maize or sorghum reached full dent stage, plant height (from soil to the bottom of the tassel) and plant density (plants per m^2, taking the row spacing into account) of each plot was measured. Plant height (from three plants) and density measurements were taken in the two-center rows. The biomass was hand-harvested on 19 September, 27 September, and 3 October 2013 in Carrington, Prosper, and Fargo, respectively, and in 8 October 2014 in Fargo. All the plants within a length of 4.6 m in the two-center rows were hand harvested leaving a 10-cm stubble height. Biomass harvested was weighed in the field on the forage harvester scale. A sample of two plants per plot was taken for water content and forage quality analysis. Samples were dried at 70°C for about seven days until constant weight, then ground in a mill with a 1-mm size mesh. Total biomass yield was calculated for each plot, using the following calculation.

Total plot biomass yield = (sample dry weight x harvested weight of the biomass)/ fresh sample weight) x total plot area/area harvested

Forage quality parameters such as crude protein (CP), starch, ether extract (EE), water soluble carbohydrates (WSC), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), neutral detergent fiber digestibility (NDFD), in-vitro dry matter digestibility (IVDMD), and ash content were determined using near infrared reflectance spectroscopy (NIRS) (Foss-Sweden Model 6500, Minneapolis, MN) in Dr. Dan Undersander's laboratory (University of Wisconsin, Madison, WI), following the method described by Abrams et al. (1987). Relative Feed Value (RFV) and relative forage quality (RFQ) were then calculated according to Undersander nd Moore (2004). Hemicellulose (HCEL) and cellulose (CEL) content were determined arithmetically where:

$$HCEL = NDF - ADF$$

$$CEL = ADF - ADL$$

The N uptake in each treatment was determined from CP content. The CP levels were obtained from the NIRS results. Total N was calculated applying the equation CP= total N x 6.25 (Kjeldahl method). Nitrogen uptake was calculated arithmetically multiplying the biomass yield in kg ha^{-1} by the N concentration in the tissue.

Specific biogas yield (SBY) was estimated from forage quality parameters with the prediction equation developed by Rath et al., (2013). This equation was developed to test maize biogas yield potential, but it was used here to compare maize monocultures with sorghum and maize-sorghum mixtures.

$$SBY\ (l\ N\ kg^{-1}\ OM) = 644.83 - 26.78 \times ADL + 42.99 \times HCEL + 128.57 \times EE - 36.75 \times WSC$$

Where ADL= Acid detergent lignin, HCEL= Hemicellulose, EE= Ether extract, WSC= Water soluble content. Biogas yield was estimated multiplying the SBY by the organic matter biomass yield.

$$Biogas\ yield\ (m^3\ ha^{-1}) = SBY \times (biomass\ yield \times (1 - Ash\ content)$$

3.3.3. Land Equivalent Ratio (LER)

According to Yu et al. (2015), LER can be calculated by,

$$LER = (Y1/M1) + (Y2/M2)$$

Where Y1 and Y2 are the yields (per unit of total area of the intercrop) of species 1 and 2 in the intercrop, and M1 and M2 are the yields of the species in sole crops (per unit area of the respective sole crop).

3.3.4. Statistical Analysis

Statistical analysis was conducted using standard procedures for a randomized complete-block design. Each location-year combination was defined as an "environment" and considered a random effect in the statistical analysis. The different cropping systems were considered fixed effects. Mean separations were performed with *F*-protected LSD comparisons at the $P \leq 0.05$ probability level, except for LER where $P \leq 0.1$was used. Analysis of variance and mean comparisons were conducted using the Mixed Procedure of SAS (SAS Institute Inc., 2014). Error mean squares were compared for homogeneity among environments according to the folded *F*-test and if homogeneous, then a combined ANOVA was performed across environments.

3.4. Results and Discussion

3.4.1. Climatic and Soil Characteristics

A typical growing season in North Dakota extends from April to early October. The 2013-2014 seasonal temperatures were very close to normal from May 2013 to October 2013 for Fargo, Prosper, Carrington, and May 2014 to October 2014 for Fargo (Fig. 3.1a, 1b, 1c, 1d). Rainfall excess for the month of May, in 2013 was 98, 46, and 36% at Fargo, Carrington, and Prosper, respectively. For the month of June, 2014 Fargo had 42% excessive rainfall. These situations resulted in adequate soil water content for plant establishment in all environments. However, in Fargo, a rainfall deficit of 63 and 81% was observed for the months of July and August of 2013, respectively and 52 and 43% for the same months in 2014. The situation in Carrington and Prosper was similar, for the same months in 2013. Carrington showed a rainfall deficit of 55 and 79% for the months of July and August, respectively, while Prosper had a rainfall deficit of 77 and 24% for the same months, 2013.

Initial soil test results (Table 3.1) showed that, soil NO_3-N was varied between years and among locations, with Carrington in 2013 recording the lowest. Available P and K in the soils from Carrington were low compared with other locations. In both years, Fargo soils had the highest organic matter content.

3.4.2. Biomass Yield, and Plant Height

The combined analysis of variance across all environments showed differences among treatments ($P<0.05$) for biomass yield, plant height, N uptake, specific biogas yield (SBY), biogas yield (BGY), and land equivalent ratio (LER) (Table 3.2). Environment by treatment interaction was significant for biomass yield, plant height, N uptake, SBY, and BGY, except LER. However, results were not discussed since the environment' was considered, random.

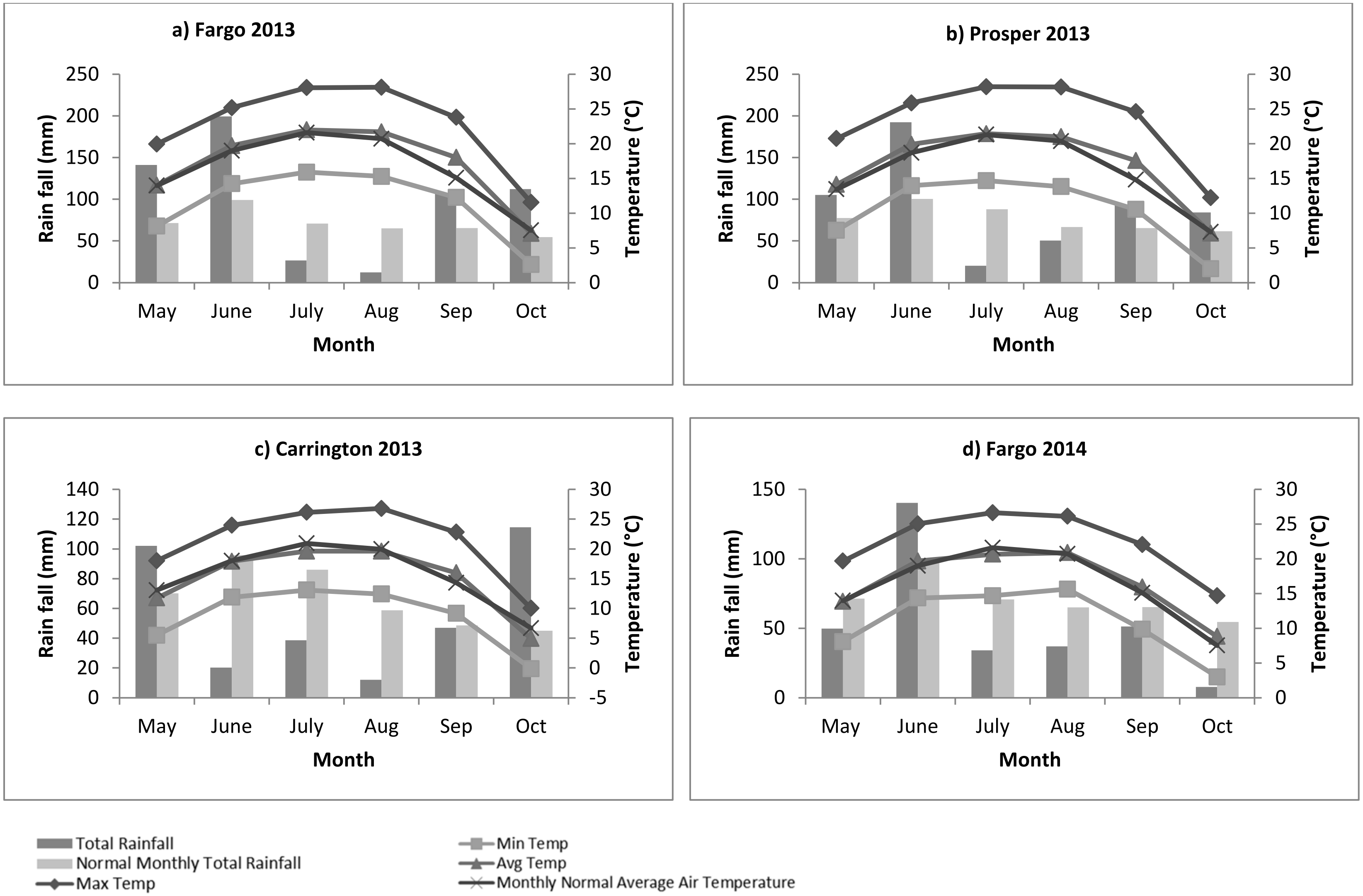

Fig. 3.1. Rainfall, 30-yr normal monthly total rainfall, maximum minimum and average temperature, and monthly 30-yr normal average air temperature; a) Fargo, ND 2013, b) Prosper, 2013, ND c) Carrington, ND, 2013, d) Fargo, ND, 2104.

Table 3.1. Initial soil analysis for experimental sites at Fargo, Carrington, and Prosper, ND in 2013 and 2014.

Environment	pH	OM[†]	P	K	NO_3-N
		%	-----mg kg^{-1}----		kg NO_3-N ha^{-1}
2013					
Fargo	7.8.	6.3	19.8	423.8	37.6
Prosper	7.7	4.3	22.8	276.3	37.6
Carrington	6.2	4.6	8.0	187.5	17.5
2014					
Fargo	7.9	7.5	10.1	406.6	36.3

[†]OM: Organic matter

Table 3.2. Analysis of variance and mean squares of biomass yield, plant height, N uptake, specific biogas yield (SBY), and biogas yield (BGY), for twelve treatments containing monocultures and intercrops, and land equivalent ratio (LER) for eight treatments containing intercrops across four environments at Fargo, Carrington, and Prosper, ND in 2013 and 2014.

Sources of variation	df	Biomass yield	Plant height	N uptake	SBY	BGY	df	LER
Env	3	814.4***	3.85***	149133***	76853***	653***	3	2.76**
Rep(Env)	8	15.3	0.24***	5571***	3871	11	8	0.23**
Treatment	11	56.6**	2.27***	15035***	14872***	51***	7	0.15
Env x treatment	33	18.7***	0.16***	4713***	5709***	17***	21	0.08
Error	195	5.7	0.03	1265	1804	5	56	0.06
CV, %		16.2	8.61	16	4	16		22.3

*, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

Biomass yield varied between 12.8 to 17.7 Mg ha^{-1} when averaged across all environments (Table 3.3). Biomass yield of silage maize (C2) and forage sorghum (S1) monocultures were not significantly different (P<0.05) when averaged across environments. Biomass yield of mixtures containing forage sorghum (S1) and silage maize (C2) were similar (P<0.05) to their respective monocultures, and also to the grain maize (C1)-forage sorghum within-row treatment (C1 x S1). Inter-row or within-row mixture arrangements, except forage sorghum (S1) within-row with both grain (C1 x S1) and silage maize (C2 x S1), did not have a difference indicating that any other combination of mixture would have a similar biomass yield. The non-BMR forage sorghum hybrid had a similar biomass yield potential to that of silage or grain maize. Thus, biomass yield is not a limitation to replace maize by forage sorghum for silage production. As expected, the BMR brachytic forage sorghum (S2) had lower yield in monoculture or in any of the mixtures. This forage sorghum is a dwarf cultivar developed to enhance forage quality and not biomass yield. The non-BMR sorghum hybrid had a similar yield potential to that of maize silage or grain. This yield was similar to yields obtained in Samarappuli et al. (2014) in similar conditions.

As expected BMR brachytic dwarf forage sorghum (S2) monoculture had lowest (P<0.05) plant height among all treatments (Table 3.3). Monoculture and all the inter-row or within-row mixtures containing the non-BMR sorghum hybrid (S1) recorded the highest plant height values compared with all other monocultures and mixtures without the non-BMR sorghum hybrid.

Annual C4 grasses such as maize and sorghum have a higher dry matter accumulation during the early stages of the developments due to the higher ability for interception of radiation (Sawyer et al., 2010; Borghi et al., 2012).

Table 3.3. Mean biomass yield, plant height, N uptake, specific biogas yield (SBY), and biogas yield (BGY), at harvest for treatments containing grain maize (C1), silage maize (C2), forage sorghum (S1), and brachytic dwarf forage sorghum (S2) arranged as monocultures (C or S), and inter-row (C + S) and within-row (C x S) intercrops, averaged across four environments at Fargo, Carrington, and Prosper, ND in 2013 and 2014.

Treatment	Biomass yield	Plant height	N uptake	SBY	BGY
	Mg ha^{-1}	m	kg ha^{-1}	[†] $l_N kg^{-1}$ OM	Nm^3 ha^{-1}
C1	14.9	1.97	197.4	1014.9	14.9
C2	16.1	2.17	216.4	1042.2	16.2
S1	17.7	2.40	298.1	961.2	16.4
S2	12.8	1.24	219.5	1011.2	12.4
C1 + S1	14.8	2.41	231.5	964.3	13.9
C1 + S2	13.2	1.72	203.6	960.4	12.3
C2 + S1	15.1	2.39	227.9	982.1	14.6
C2 + S2	12.8	1.93	210.9	1014.5	12.6
C1 x S1	16.8	2.31	251.2	973.2	15.9
C1 x S2	13.9	1.90	214.1	951.5	13.0
C2 x S1	16.3	2.30	250.1	986.4	16.1
C2 x S2	12.9	2.05	209.1	994.8	12.7
LSD (*P*=0.05)	2.7	0.25	43.2	47.5	2.6

[†] specific biomass yield (SBY), biogas yield (BGY). OM=Organic matter.

Using intercrops containing maize and sorghum allows high biomass production (Borghi et al., 2012). Weed pressure may also be reduced by having an intercrop with such high competing nature, as a biological/cultural control method. Mahmood et al. (2013b), reported on substantial reduction in, both population and dry matter of purple nutsedge (*Cyperus rotundus* L.) by an intercropping system containing maize and sorghum.

3.4.3. Nitrogen Uptake

Nitrogen uptake values for the twelve different treatments ranged between 197.4 to 298.1 kg ha^{-1} (Table 3.3). The non-BMR sorghum hybrid (S1) recorded the highest (P<0.05) N uptake, which was higher than all other treatments. Plant N uptake is calculated by multiplying the plant N content by its biomass. Therefore, it is expected that mixtures containing forage sorghum (S1), would have higher N uptake values with its higher biomass. Even though the biomass yields of silage maize (C2) and forage sorghum (S1) monocultures were not significantly different (P<0.05), the N uptake value of S1 was higher than that of C2 when averaged across environments. This may be due to the increased ability of sorghum to extract N from soil, compared with maize (Sindelar et al., 2016). Sweet sorghum is highly efficient in extracting soil N and was able to extract 80 kg N ha^{-1} from the soil at its highest level of biomass production when grown in a low fertile marginal soil. As a result, the need for N inputs is relatively low to optimize yield, even in marginal environments (Sindelar et al., 2016). In a study conducted by Zotarelli et al. (2009), sweet corn was only able to extract less than 20 kg N ha^{-1} under conditions grown on marginal sandy soil.

In order to sustain the long term soil fertility, cropping systems with sorghum would need strategies to replace soil N removed by the crop to avoid depletion of soil organic N, thus degradation of the soil. The ability to take up high amounts of soil N, may be important in reducing soil N content. Intercropping forage sorghum could be a useful strategy to reduce the N leaching potential, compared with having a maize monocrop (Hermann and Taube, 2005; Solltz and Nadeau, 2014).

Nitrogen uptake by plants increases as soil water availability increases (Schittenhelm 2010). It can be argued that the observed higher N uptake by forage sorghum may have also been due to its ability to take water up, even with a low supply. Forage sorghum can be used for silage where rainfall limits maize growth, less than 350 mm per year (Undersander et al., 2010).

3.4.4. Specific Biogas Yield

Specific biogas yield (SBY) fluctuated between 951 and 1042 l_N kg^{-1} OM. Highest specific biogas yield resulted from monocultures of maize grain (C1) and silage (C2), BMR forage sorghum (S2), and inter-row mixture containing silage maize (C2) and BMR sorghum (S2) (Table 3.3).

This result is very interesting because adding a BMR sorghum to the mix with maize increases feedstock degradability and biogas productivity. The prediction equation, although developed for maize, was able to detect a greater SBY in the BMR cultivar as expected. The BMR forage sorghum SBY was 50 lN kg^{-1} OM greater than the non-BMR sorghum. The average lignin content was 58 g kg^{-1} for the BMR sorghum and 68 g kg^{-1} for the non-BMR forage sorghum (data not shown). Previous researchers consistently have reported a negative effect of lignin on feedstock degradability (Mahmood et al., 2013a; Rath et al., 2013), which explains the greater SBY of the BMR sorghum (S2) compared with the non-BMR sorghum (S1).

Specific biogas yield reported for maize fluctuated between 706 and 909 lN kg^{-1} OM (Oslaj et al., 2010; Mahmood et al., 2013a) and 487 and 720 lN kg^{-1} OM for sorghum (Mahmood et al., 2013a). These values are lower than the values estimated in our study. The main reason for this difference was higher HCEL content of the samples in our study (190-230 g kg^{-1}). The prediction model used by Rath et al. (2013) reported a mean value of 137 g kg^{-1} of HCEL with a fluctuation of 113 to 168 g kg^{-1}. All other parameters in the prediction equation ADL, EE, and WSC were within the same range as those used to developed the model (Rath et al., 2013).

3.4.5. Biogas Yield

Biogas yield ranged from 12 300 to 16 400 Nm^3 ha^{-1} (Table 3.3). Other authors have reported similar biogas yield for maize (12 606 – 16 447 Nm^3 ha^{-1}) (Oslaj et al., 2010; Mahmood et al., 2013, Rath et al., 2013) and for forage sorghum (7 649 – 12 880 Nm^3 ha^{-1}) (Mahmood et al., 2013a).

Monoculture of grain maize (C1) and silage maize (C2) biogas yield was similar to that of forage sorghum (S1) monocultures and mixtures containing forage sorghum (S1). The mixtures arrangement, inter-row or within-row, did not have an effect on biogas yield. The species and cultivar used were the determining factor on biogas yield.

These results indicate biomass yield or biogas yield are not limitations to replace maize by forage sorghum for silage and biogas production. Previous studies conducted in Germany have reported that forage sorghum can be competitive with maize for energy production (Mahmood et al., 2013a). Incorporating sorghum into maize could avoid problems such as decreasing crop diversity, increased loss of nutrients, and increased pest incidences, due to maize monocultures (Schittenhelm, 2010).

3.4.6. Land Equivalent Ratio

All the intercrop mixtures except for inter-row mixtures with grain maize (C1), showed LER values greater than 1 (Table 3.4), indicating that those treatments produced biomass more efficiently than monocultures. According to the results, within-row mixtures containing silage maize had a higher ($P \leq 0.1$) LER value than that of the inter-row mixtures with grain maize and non-BMR forage sorghum (C1 + S1). Even though the two within-row mixtures containing silage maize had a similar LER value, the treatment containing silage maize with non-BMR sorghum (C2 x S1) had a higher ($P \leq 0.05$) biomass yield than the treatment containing silage maize with BMR sorghum (C2 x S2) (Table 3.3). Within-row mixtures containing silage maize (C2), was approximately 20% more efficient in producing biomass, than monocultures thus, 20% more biomass can be produced in the same land area, compared to each of the species planted as monocultures (Bybee-Finley et al., 2016). In this study, however, the result was opposite since monocultures of silage maize (C2) and non-BMR sorghum (S1) reported similar biomass yields to that of the within-row mixture of silage maize and non-BMR sorghum (C2 x S1) . Furthermore, within-row mixture of silage maize and BMR sorghum (C2 x S2) had the lowest biomass yield, which was lower than silage maize (C2). Such abnormalities might be the result of poor performance of the monocultures involved (Bybee-Finley et al., 2016). However in addition to biomass production, intercropping is expected show other benefits such as improving soil health, pest and disease suppression, and climate change mitigation (Lin, 2011). Yield stability and resilience of a cropping system will improve with the crop diversity, specially faced with adverse weather conditions (Gaudin et al., 2015; Sindelar et al., 2016). This may be a factor resulting in similar yields in mixtures that had a lower than normal rainfall during the months of July and August in all four environments.

3.4.7. Forage Quality Components

The combined analysis of variance across all environments showed differences among treatments ($P < 0.05$) for several forage quality parameters such crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), neutral detergent fiber digestibility (NDFD), in vitro dry matter digestibility (IVDMD), total digestible nutrients (TDN), and relative feed quality (RFQ) (Table 3.5).

Crude protein was greater ($P \leq 0.05$) in forage sorghum monocultures compared with maize monocultures, but similar to that of inter-row mixture containing silage maize and BMR forage sorghum (C2 + S2) (Table 3.6). Maize monocultures had the lowest CP levels, which were lower ($P \leq 0.05$) than to the mixtures containing maize and sorghum. On average, monocultures of forage sorghum showed 20% higher CP content than maize monocultures.

Table 3.4. Mean land equivalent ratio values for biomass at harvest for treatments containing grain maize (C1), silage maize (C2), forage sorghum (S1), and brachytic dwarf forage sorghum (S2) arranged as inter-row (C + S) and within-row (C x S) intercrops, averaged across four environments at Fargo, Carrington, and Prosper, ND in 2013 and 2014.

Treatment	LER†
C1 + S1	0.9
C1 + S2	1.0
C2 + S1	1.1
C2 + S2	1.1
C1 x S1	1.1
C1 x S2	1.1
C2 x S1	1.2
C2 x S2	1.2
LSD *(P=0.1)*	0.2

† Land equivalent ratio (LER).

Mixtures other than C2 + S2, had a 12% higher CP content, compared with maize monocultures. Anil et al. (1998), also reported higher CP levels for maize intercrops compared to maize monocultures. Generally, it is considered that maize has a comparable or higher CP content compared with sorghum (Miron et. al., 2007; Undersander et al., 2010). However, in our study, the CP content of sorghum monocultures averaged 104 g kg^{-1}. Bean and Marsalis (2012) reported CP content for forage sorghum between 46 and 93 g kg^{-1}.

Crude protein content decreases in mature vegetation as hydrolyzing enzymes break down the higher molecular weight compounds to lower molecular weight components such as amino acids, amines, and amides (Mengel and Kirkby, 1982). These N containing compounds are transported through the xylem as NO_3, NH_4 and amino acids into the root system, decreasing the CP content in the aboveground biomass as the crop senesces. Since the experiments were harvested before senescence (while they were still green and with approximately 70% moisture content) this could explain the higher CP values obtained in forage sorghum.

Maize monocultures had the lowest ($P \leq 0.05$) ash content among all treatments, which was less than half to that of sorghum monocultures (Table 3.6). Mixtures had a similar ash content, which was 27% higher and 33% lower, than that of maize and forage sorghum monocultures, respectively. Ash content is comprised of soil particles or dust on the plant, and also from several important plant nutrients such as Si, K, Ca, S, and Cl (Bakker and Elbersen, 2005).

According to Smith (1960) Ca, K, and tissue ash content in cereal crops decreases from early growth stages until early-dough stage, creating a higher ash content at soft-dough stage when the cereal crops are harvested. Forage sorghum and maize were harvested at the same time. Thus most of the mineral nutrients probably had time to mobilize back to the soil before harvest in maize which was at full-dent stage, compared with sorghum, which was at hard-dough stage.

Efficiency in the process of converting biomass to biogas is impacted by ash content, as ash is unable to be fermented in the production process and an excess can inhibit anaerobic microorganisms growth (Sanderson et al., 2006). Therefore, lower ash content in mixtures, compared with forage sorghum monocultures make them better candidates as biogas feedstock.

Maize monocultures and mixtures had a similar NDF, ADF, and ADL content which was lower than that of non-BMR forage sorghum (S1) (Table 3.6). Interestingly, the BMR brachytic dwarf forage sorghum (S2) monoculture had lower NDF, ADF, and ADL content, than the non-BMR forage sorghum (S1), but similar to that of silage maize monoculture (C2)..

Table 3.5. Analysis of variance and mean squares of forage quality analysis, starch, and N content for twelve treatments containing monocultures and intercrops across four environments (Env) at Fargo, Carrington, and Prosper, ND, in 2013 and 2014.

Sources of variation	df	CP[†]	Ash	NDF	ADF	ADL	NDFD	IVDMD	TDN	RFQ	Starch content	N content
Env	3	5.9***	9.1***	248.2***	103.4***	10.7***	547.7***	24.1	3759.1***	259223.2***	386.3***	0.15***
Rep(Env)	8	1.5*	1.0	18.7	10.9	0.6	5.1	12.3	22.1	1416.1	33.4	0.04
Treatment	11	8.7**	20.6***	192.4***	111.9***	8.2***	40.6***	104.6***	247.7***	14010.0***	558.3***	0.22***
Env x Treatment	33	0.8*	0.9	27.5***	13.1***	1.0***	17.5***	8.4	74.3***	7375.8***	40.9	0.02
Error	195	0.5	0.5	9.8	4.5	0.3	6.7	5.0	6.5	480.4	20.2	0.01
CV, %		7.3	16.1	6.1	7.5	10.5	3.6	2.8	3.6	11.9	38.3	7.36

*, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

[†]Quality parameters: crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), neutral detergent fiber digestibility (NDFD), in vitro dry matter digestibility (IVDMD), total digestible nutrients (TDN), relative feed quality (RFQ).

The component NDF is an estimation of total cell wall components; which are mainly cellulose, hemicellulose, lignin, and Si Acid detergent fiber content indicates the cellulose and lignin components of the cell wall while the ADL content indicates the lignin component (NRC, 2001). Therefore, when ADF increases, forage digestibility decreases. Also, higher lignin content in the biomass decreases the digestibility of cellulose and hemicellulose (Traxler et al., 1998). McCollum et al. (2010), suggested that if the lignin content of a forage can be lowered, as a result, the ADF fraction could become more digestible and the energy value of the forage would be increased. Results indicate that mixtures containing maize and forage sorghum are similar to the fiber content found in maize, which is widely used to feed lactating dairy cows, thus providing a comparable alternative to maize. Brachytic dwarf forage sorghum monoculture (S2), had a similar NDFD content compared with maize monocultures (C1 and C2), and was higher than that of non-BMR forage sorghum (S1) (Table 3.6). While most mixtures that contained the non-BMR forage sorghum (S1) had lower NDFD values compared with those with brachytic dwarf forage sorghum (S2), the within-row mixture containing silage maize and non-BMR forage sorghum (C2 x S1) was not different than C2 x S2. Furthermore, the lowest ($P \leq 0.05$) IVDMD was in the non-BMR forage sorghum monoculture (S1) (Table 3.6). Monoculture and mixtures containing the BMR forage sorghum (S2) had higher IVDMD levels, compared with maize monocultures. The higher digestibility in monoculture and mixtures containing BMR forage sorghum is mostly likely due to the, reduced lignin content associated with the BMR character (Miron et al., 2007). Higher estimated milk production with BMR forage sorghum was reported in studies conducted by Marsalis et al. (2008). Total digestible nutrient content in silage maize monoculture (C2) was lower ($P \leq 0.05$) than the grain maize monoculture (C1), and similar to that of BMR forage sorghum (S2) (Table 3.6).

Table 3.6. Mean plant tissue nutritional quality parameters at harvest for treatments containing grain maize (C1), silage maize (C2), forage sorghum (S1), and brachytic dwarf forage sorghum (S2) arranged as monocultures (C or S), and inter-row (C + S) and within-row (C x S) intercrops, averaged across four environments at Fargo, Carrington, and Prosper, ND in 2013 and 2014.

Treatment	CP[†]	Ash	NDF	ADF	ADL	NDFD	IVDMD	TDN	Starch	N	RFQ
	----------------------	----------------------	----------------------	----------------------	----------------------	g kg^{-1}	----------------------	----------------------	----------------------	----------------------	
C1	80.6	31.0	495.9	267.2	48.5	730.6	786.6	757.6	163.2	12.9	198.7
C2	85.6	31.7	523.2	286.1	48.7	723.5	783.2	710.7	128.1	13.7	171.6
S1	103.5	63.2	571.6	330.6	67.6	700.6	757.7	653.1	9.5	16.6	153.5
S2	104.5	65.2	541.5	303.8	57.6	739.9	807.9	676.6	22.9	16.7	165.8
C1 + S1	96.7	44.3	500.9	274.1	51.3	705.3	800.1	719.7	144.9	15.5	183.1
C1 + S2	95.7	45.0	469.9	252.1	45.1	743.2	825.2	761.7	168.2	15.3	208.1
C2 + S1	93.2	42.1	523.9	290.4	53.5	719.4	780.5	707.9	114.1	14.9	176.0
C2 + S2	100.4	46.6	506.4	276.3	46.5	739.0	809.7	725.6	120.5	16.1	188.9
C1 x S1	91.6	43.6	515.1	284.5	52.1	717.6	791.0	714.5	138.5	14.6	177.8
C1 x S2	94.3	41.6	456.9	242.1	45.1	731.7	841.7	770.3	184.5	15.1	211.0
C2 x S1	91.7	42.1	528.9	293.7	54.1	719.0	780.2	710.8	104.9	14.7	170.4
C2 x S2	97.2	41.8	489.9	265.2	45.4	744.4	815.6	750.5	132.7	15.6	203.6
LSD (*P*=0.05)	5.5	6.1	32.9	22.7	6.3	26.3	18.2	54.2	40.2	0.9	54.1

[†]Quality parameters: crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), neutral detergent fiber digestibility (NDFD), in vitro dry matter digestibility (IVDMD), total digestible nutrients (TDN), relative feed quality (RFQ).

This was expected, since the grain in maize would have added more soluble nutrients to the silage mix. The lowest TDN was obtained in the non-BMR forage sorghum monoculture (S1) treatment. All the mixtures except for the inter-row mix of silage maize and non-BMR forage sorghum (C2 + S1), reported similar TDN levels which were higher than that of the non-BMR forage sorghum monoculture (S1) treatment. Inclusion of grain maize (C1) into silage mixes with non-BMR forage sorghum monoculture (S1) increases TDN, compared to the non-BMR forage sorghum monoculture.

Maize monoculture treatments had higher ($P \leq 0.05$) starch content than the forage sorghum monocultures (Table 3.6). But with the inclusion of grain maize into forage sorghum, this resulted in elevated starch levels in those mixtures, which are similar to that of grain maize monoculture. Maize was at full dent stage at the time of harvest which resulted in higher grain portion going into the sample explaining the higher starch content in grain maize monoculture and mixtures.

The highest N content of the biomass was in forage sorghum monoculture and the inter-row mixture containing silage maize and BMR forage sorghum (C2 + S2) (Table 3.6). Among all treatments, those without forage sorghum and maize monocultures (C1 and C2) had the lowest N content. These results further proof that, forage sorghum is better at taking up N from the soil, even at a low fertility rate, such as the 80 kg N ha^{-1} used in the study.

There were no significant differences among maize-forage sorghum mixtures, for RFQ (Table 3.6). Relative forage quality has been used to rank hay quality, and also to assign forage to animal groups according to their quality needs. Since RFQ calculation considers both TDN, and the dry matter intake, it predicts the forage quality better than the traditional relative feed value (RFV) (Undersander and Moore, 2004). Forage with a RFQ value of 151 or higher, is considered to have the highest forage quality and categorized as ‘premium’ in the USA Midwest, and generally for high-producing dairy cows and young calves (Hancock, 2011). All the treatments resulted in RFQ values within the range of 153 and 211, thus can be categorized as premium quality. By combining maize and forage sorghum, this study was able to provide forage with improved quality.

3.5. Conclusion

Maize is considered the most widely used forage for dairy cows in the northern USA. Non-BMR forage sorghum was able to produce high biomass yields, similar to that of maize. Incorporation of non-BMR forage sorghum into maize as an intercrop also had similar yield to that of maize monocrop systems. Forage sorghum dwarf variety with the BMR trait did not provide similar yield compared with the non-BMR forage sorghum; however the forage quality was improved. Mixtures containing non-BMR forage sorghum and maize were able to produce high quality forage, with relative forage quality values exceeding 151. Intercrop mixtures consist of maize and forage sorghum have the potential to be more efficient than their monocultures in producing biomass.

Biogas yields similar to maize can be obtained from non-BMR forage sorghum monoculture and with mixtures containing maize and non-BMR forage sorghum. Concerns of reduced biomass or biogas yields are not limitations to replace maize by sorghum for biogas production. Considering the ability of forage sorghum to be more productive in environments with low fertility and less available water compared with maize, intercropping systems consists of forage sorghum and maize could provide an option to have more resilient and stable, forage, and biogas production system in the US Midwest.

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CHAPTER 4. INTEGRATING WINTER CAMELINA INTO MAIZE AND SOYBEAN CROPPING SYSTEMS

4.1. Abstract

Camelina [*Camelina sativa* (L.) Crantz.] is an industrial oilseed crop in the Brassicaceae family with multiple uses. Currently, camelina is not being used as a cover crop, but it has the potential to be used as such in maize (*Zea mays* L.) -soybean [*Glycine max* (L.) Merr.] cropping systems. The objective of this study was to determine the agronomic performance of winter camelina intersown as a cover crop into standing soybean or maize crops prior to their harvest. Experiments were conducted in Fargo, ND in 2014, Prosper, ND, in 2015, and in Morris, MN in 2014 and 2015. The experimental design was a randomized complete block design with a split-plot arrangement with three replicates. The main plot was row spacing (61 and 76 cm in maize, and 31 and 61 cm in soybean) while the sub-plot was maize or soybean growth stage at intersowing of camelina. Winter camelina was sown on four different dates: Date 1 (SD1), at the same sowing date as maize and soybean, Date 2 (SD2) at V4-V5 of maize and V3-V4 of soybean growth stages, Date 3 (SD3) at 'silking' of maize and R1-R2 stage of soybean, and Date 4 (SD4) after maize and soybean harvest. Camelina establishment into standing maize and soybean largely depended on rainfall after sowing. Camelina intersown on SD1 resulted in lower maize and soybean grain and biomass yield of 14 and 10%, respectively, whereas intersowing after SD2 had no significant effect. Camelina potential N uptake (based on 100% cover) varied between 24 and 59 kg N ha^{-1} and potential P uptake ranged between 4.3 and 9.2 kg P ha^{-1} in the spring when sown after maize and between 14 and 57 kg N ha^{-1} and 1.5 and 6.9 kg P ha^{-1} when sown after soybean. Results indicate that camelina intersown after V4-V5 of maize or V3-V4 of soybean stages will likely avoid competition with the primary cash crop. Camelina establishment

and winter survival was best when sown after maize and soybean harvest, and tended to be greater in soybean. However, there are many unanswered questions on camelina intersowing management. New research will allow optimization of intersowing management to increase yields of both crops while enhancing ecosystem services.

Keywords: Intersowing, intercropping, cover crops, nutrient scavenging, cropping systems

4.2. Introduction

The use of cover crops, common in the eastern and central US states, are uncommon in maize-soybean systems in the Upper Midwest and northern Great Plains (NGP) of the USA, due to the short growing season and extreme fluctuations in temperature and rainfall within and across growing seasons. Lack of winter soil cover increases soil organic matter and nutrient losses, resulting in decreased crop productivity and resiliency. For these reasons, larger amounts of agricultural inputs are required to maintain or increase yields. Therefore, there is a critical need to alter current cropping systems in our region by incorporating technologies to improve long-term productivity while enhancing ecosystem services. Generally, broadleaf cover crops do not survive most winters in the NGP region, even when drilled in later summer to early autumn. Therefore, identifying new winter-hardy broadleaf cover crops is necessary for their incorporation into the NGP cropping systems.

Camelina seed meal and oil have multiple uses an applications as feedstock for biofuel, animal feed, human food, and many more (Berti et al., 2016). Camelina has been grown since 4000 BC, although it is not a well-known or widely produced crop. In the last 10 years, abundant new research in camelina uses, genetics, and agronomic management have been published indicating great interest and potential of this crop due to product end-use diversity (Berti et al., 2016).

One new potential use of camelina is as a cover crop in maize-soybean rotations in the Midwest USA. Winter camelina can be direct-sown following the harvest of short-season cereals such as wheat (*Triticum aestivum* L.) (Gesch and Archer, 2013; Berti et al., 2015) and it has the potential to be established by broadcasting into longer season standing crops such as maize and soybean.

Integrating winter camelina into maize-soybean cropping system will likely increase biodiversity, and reduce: i) soil erosion, ii) NO_3-N leaching, iii) P run-off, and iv) production input costs, while maintaining or improving the yield of the primary cash crop.

Winter camelina is very winter hardy and has been demonstrated to be successfully double- and relay-cropped with soybean and forage sorghum [*Sorghum bicolor* (L.) Moench] (Gesch et al., 2014; Berti et al., 2015). In the NGP, winter camelina can be sown during fall (between early-September to mid-October) after a cereal crop harvest. It germinates even when soil temperatures are as low as $1^{o}C$ (Gesch and Cermak, 2011). Plants established in the autumn remain in the rosette stage over winter and resume growth the following spring after which they bolt, flower, set seed, and mature in early summer (Grady and Nleya, 2010).

Planting a cover crop in conventional maize-soybean production systems in the northern regions of the USA is challenging due to the narrow establishment window, short growth period, and limited soil water availability (Bich et al., 2014). In areas with longer season, cover crops can be sown by drilling or aerial broadcasting after harvesting the primary cash crop (Wilson et al., 2014). Unfortunately, when cover crops are broadcasted, establishment depends largely on rainfall shortly after sowing and if not received, the probability of failed stand establishment increases (Fisher et al., 2011).

In order to improve establishment of cover crops, many researchers have started investigating the establishment of cover crops by intersowing at early growth stages of maize (V4-V8). Intersowing of cover crops or legumes in winter wheat has been evaluated in Europe (Bergkvist et al., 2011). Most studies report no penalties on grain yield on wheat or oat (*Avena sativa* L.) when cover crops are intercropped into the cereal crop (Bergkvist et al., 2011; Amossé et al., 2013; Neugschwandtner and Kaul, 2014). In maize-soybean systems, most research on intersowing has been done in organic production systems in an effort to reduce weed pressure without decreasing grain yield (Baributsa et al., 2008; Belfry and Van Eerd, 2016).

Intercropping camelina into standing cash crops is not common. However, mixed cropping of camelina, with pea (*Pisum sativum* L.), lupin (*Lupinus angustifolius* L.), or wheat was evaluated in an organic cropping system by Paulsen (2007), in Germany. Both crops were grown and harvested together to be sorted by seed size screening post-harvest. Overall yields of mixed cropping with camelina were similar or lower than the sole crop. Camelina was able to fill gaps on grain legume establishment for a higher total yield of both crops as compared with the total yield of sole legumes (Paulsen, 2008). Winter camelina was intercropped with barley (*Hordeum vulgare* L.) in Lithuania in an organic system to reduce weed pressure. After drilling camelina in strips between the rows of barley, weed density decreased by 1.79 times (Raslavicius and Povilaitis, 2013). Additionally, camelina can be grown in mixtures with flax (*Linum usitatissimum* L.), rape (*Brassica napus* L.), or safflower (*Carthamus tinctorius* L.) to produce on farm-biodiesel (Paulsen, 2008, 2011).

Economic returns play a critical part in evaluating a cropping system, especially if it is an unconventional and novel system. For an economic analysis, difference in yields, value of the crops, and input costs need to be taken in to account. Performing a sensitivity analysis is considered an important tool for determining the costs of a cropping system, with changing costs and prices (Rafiee et al., 2010; Jahanzad et al., 2015). Adding a cover crop to a cropping system increases production costs due to the additional establishment costs, indirect costs due to the management of some cover crops, and opportunity costs of reduced income due to cash crop yield losses incurred from delayed planting, competition, or replacement by cover crops (Snapp et al., 2005). However, a value of cover crops can be calculated by assigning a dollar value to reducing soil losses due to erosion, reduction in nitrate leaching, and nutrient credits (Roth et al., 2016). In a survey conducted by Singer et al. (2007), 96% of growers in the US Corn Belt region believe cover crops are effective in reducing soil erosion and 74% recognized cover crops to increase soil organic matter content. Even if growers value such benefits, some growers consider it is too expensive and they cannot see returns on the investment (Snapp et al., 2005). Therefore, Singer et al. (2007) calculated how much the minimum payment growers would agree to plant cover crops. The mean minimum payment according to this survey was \$57 ha^{-1} as an incentive to plant cover crops.

Intersowing of winter camelina into standing maize and soybean as a cover crop in the establishment season, have not been previously studied. The objectives of this study were i) to determine the overall agronomic performance of intersowing winter camelina as cover crop into a standing soybean and maize crop in order to provide soil cover in late fall and early spring, and recycle nutrients ii) to estimate the economic impact of intersowing camelina into maize and soybean.

4.3. Materials and Methods

4.3.1. Field Description and Management

Experiments were conducted at two North Dakota State University (NDSU) research sites at Fargo, ND (46° 89’ N,-96° 82’ W, 274 m elevation) in 2014, and Prosper, ND (46°58’ N, -97° 3’W, elevation 284 m) in 2015, and at the Swan Lake Research Farm, Morris, MN (45° 35’N, -95° 54’W, elevation 344 m) in 2014 and 2015. The soil type in Fargo was a Fargo silty clay soil (fine, montmorillonitic, frigid, Vertic Haplaquoll, with a leached and degraded nitric horizon), while the soil in Prosper was a Kindred-Bearden silty-clay loam (Perella: fine-silty, mixed, superactive Typic Endoaquoll; Bearden: fine-silty, mixed, superactive, frigid Aeric Calciaquoll). The soil type at Morris was a Barnes loam soil (fine-loamy, mixed, superactive, frigid Calcic Hapludoll). The previous crop at all three locations was either oat or soybean and the experimental plots were not tilled.

Daily temperature and rainfall were recorded by the North Dakota Agriculture Weather Network (NDAWN) system at Fargo and Prosper and by an automated weather station at the Swan Lake Research Farm. Soil samples were taken at all locations for analysis at the beginning of each experiment in 2014 and 2015 at both locations before the crops were sown. Soil samples were taken at a 0- to 15-cm depth and tested for pH, organic matter, P, and K, while the NO_3-N analysis was done from the soil samples taken at 0- to 15-cm and 15- to 60-cm depth.

4.3.2. Experiment Description

The experimental design was a randomized complete block design with a split-plot arrangement and three replicates. The main plot was the row spacing (61-cm and 76-cm in maize and 31- and 61-cm in soybean) and the sub-plot was the maize or soybean growth stage at the time camelina was intersown into the standing crop. Check plots of maize and soybean were not intersown with camelina. Maize and soybean were considered as separate experiments. Experimental units were 7.6 m long and 2.7 m wide and had four rows of either maize or soybean.

The maize hybrid used was 75K85 GEN VT2PRO (85 d maturity, Roundup Ready^{TM}). The soybean variety was 13R08N GEN RR2Y (maturity group 0.8, Roundup Ready^{TM}). All seeds were obtained from Peterson Farms Seeds (Harwood, ND). Winter camelina, cv. Joelle, was obtained from plants grown in Morris, MN during 2013. Sowing rates were calculated based on the percentage of pure live seed (PLS), taking purity and germination percentage into account. Soybean seeds were not inoculated nor chemically treated with a fungicide, before sowing. Targeted plant density was 86 450 and 432 250 plants ha^{-1} for maize and soybean, respectively.

Maize was sown on 22 April, and 29 April 2014 at Morris and Fargo, respectively, and on 22 May and 27 May 2015 at Morris and Prosper, respectively. Maize was sown at a depth of 50 mm (on minimum-till soil) with a 4-cone plot seeder (Wintersteiger Plotseed XL, Salt Lake City, UT) for the 61-cm row spacing and with a 4-row seeder (John Deere MaxEmerge 1730, Ankeny, IA) for the 76-cm row spacing. Soybean was sown on the same dates as maize at Morris in 2014 and 2015 and at Prosper in 2015, using the same equipment as used for sowing maize. The soybean at 31-cm spacing was sown with the same planter as for 61-cm row spacing.

Winter camelina was intersown between maize rows on four different dates: Date 1 (SD1), at the same sowing date as maize, Date 2 (SD2) at V4-V5 maize growth stage, Date 3 (SD3) at ‘silking’ maize growth stage, and Date 4 (SD4) after maize harvest. In Morris, SD2 was sown on 23 June 2014 and 22 June 2015; SD3 on 29 July 2014 and 28 July 2015, and SD4, on 1 October 2014 and 21 October 2015. In Fargo, SD2, SD3, and SD 4 were sown on 2 July, 8

August, and 8 October 2014, respectively. In Prosper, SD2, SD3, and SD4 were sown on 30 June, 9 August, and 21 October 2015, respectively.

For SD1 treatment, camelina was sown with an 8-row cone drill (Wintersteiger Plotseed XL, Salt Lake city, UT), at 15-cm row spacing right after the maize and soybean seeding and off-set by 7.5 cm from the primary crop rows. For the SD2, SD3, and SD4 in maize and soybean, camelina seed was hand-broadcasted without incorporation between the primary crop rows. Camelina sowing rate in both maize and soybean was 10 kg ha^{-1} PLS for all sowing dates. For SD1, seeds were sown to a depth of approximately 1.3 cm.

Winter camelina was sown on four different dates in soybean. Date 1 (SD1), at the same sowing date as soybean, Date 2 (SD2) at V3-V4 soybean growth stage, Date 3 (SD3) at R1-R2 soybean growth stage, and Date 4 (SD4) after soybean harvest. In Morris, SD2 was on 23 June 2014 and 22 June 2015; SD3 on 29 July 2014 and 28 July 2015; SD4 1 October 2014 and 21 October 2015. In Prosper, SD2, SD3, and SD 4 were sown on 30 June, 9 August, and 22 October 2015, respectively.

Approximately four weeks after sowing the primary crop all plots were fertilized. In both years, all maize plots in both locations were fertilized by hand broadcasting with 150 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1}, and 30 kg K_2O ha^{-1}. Soybean plots only received P and K at rates that were the same as for maize in both years.

During the study, as needed, glyphosate [N-(phosphonomethyl) glycine] was applied at 1.1 kg a.i ha^{-1} to the plots on the same day or prior to the camelina sowing to control weeds. However, glyphosate was not applied on SD4 due to very low weed pressure. No herbicides were used on plots with camelina.

When maize reached physiological maturity (R6) cobs were harvested by hand from 1 m of each of the 2-center rows of each plot and then threshed. This was done on 1 October and 8 October in 2014 at Morris and Fargo, respectively, and on 21 October 2015 at Prosper. However, in 2015, a plot combine harvester (Massey Ferguson Kincaid 8XP, Haven, KS) was used to harvest maize seed by harvesting the 2-center rows at Morris on 22 October. Maize biomass was hand-harvested in a separate 1 m of each of the 2-center rows of each plot, before harvesting the seed, leaving a stubble height of 10-cm.

Soybean seed was harvested with a plot combine harvester (Hedge 160, Wintersteiger, Salt Lake City, UT) by taking the 2-center rows of each plot in the 61-cm row spaced plots, while all four rows were harvested in the 31-cm plots. Soybean was harvested on 1 October, 2014 at Morris, and on 29 September and 20 October, 2015 at Morris and Prosper, respectively.

Stand counts of maize and soybean were recorded in 1 m^2 in the two center rows each plot before the final harvest. Plant height of soybean (from soil level to the last trifoliate leaf), and maize (from soil level to the tassel's tip) was measured taking three measurements per plot, before harvesting.

Harvested maize biomass samples were dried (70˚C for seven days), and tissue samples were then ground in a mill with a 1-mm size mesh screen. Maize ground samples were analyzed for crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), in vitro dry matter digestibility (IVDMD) and total digestible nutrients (TDN) content using near infrared reflectance spectroscopy (NIRS) (Foss-Sweden Model 6500, Minneapolis, MN) following the method described by Abrams et al. (1987). Soybean seed samples were analyzed for protein and oil content using NIRS (Perten DA7250, Perten Instruments in Springfield, Illinois) at the Northern Crops Institute (Fargo, ND).

The percent area of a plot covered with camelina plants both in maize and soybean was recorded after harvesting, following visual inspection of each plot in the fall. Spring coverage evaluation and camelina biomass was planned but only was taken at one location in two years Morris 2015 and 2016. The other two locations were accidentally tilled before evaluations of camelina survival could be taken.

Camelina spring biomass samples of 1 m^2 were taken on 9 May 2015 and of 0.09 m^2 on 25 April 2016 in Morris. Because of the high number of plots with no camelina plants or not enough biomass for analysis, only plots with plants were analyzed and compared among sowing dates. Crude protein, NDF, and N and P content were analyzed. Biomass samples were dried (70˚C for seven days), and tissue samples were then ground in a mill with a 1-mm size mesh. Camelina biomass samples were analyzed by wet chemistry. The total N content was measured with the Kjeldahl method, percentage of ash with AOAC Method 942.05, and CP and P with AOAC Method 2001.11.

The N and P uptake in all crops was determined by multiplying N and P content of the biomass by the biomass dry matter yield. Total nitrogen was calculated applying the equation CP= total N x 6.25. Nitrogen and P uptake (kg ha^{-1}) was calculated arithmetically multiplying the biomass yield by the N or P content (g kg^{-1}). The N uptake represents the potential N uptake of camelina if cover is 100%. Samples for N uptake were taken from areas with high plant density to estimate the potential N uptake, when camelina has a good stand (100% cover). Thus values of N uptake presented are not related to camelina plant cover percentages.

4.3.3. Economic Analysis

Economic analysis of each system was done, based on the crop budgets constructed. Constructed budgets were developed ha^{-1}, using financial information from Aakre, (2013) and

Swenson and Haugen (2014). Costs of production considered input expenses for land preparation, seeding, fertilizer, and pest management. Description of inputs and operations are included in Table.4.1.

Seed prices for maize and soybean were calculated using the price per thousand kernels (TK) and multiplied for a target plant density of 86 450 for maize and, 432 250 ha^{-1} for soybean, respectively. The price of soybean seed included the cost of inoculation and seed treatment. The price of camelina seed was assumed similar to that of canola (*Brassica napus* L.) seed (Keske et al., 2013).

Sowing, spraying, and harvesting equipment most commonly used in the region were used in the analysis (Table 4.1).For camelina sowing on SD1, a press-wheel grain drill was used and for broadcasting, aerial seeding was considered. Machinery costs included labor, repairs, fuel and oil, depreciation, and machinery overhead. These were based on values obtained from Lazarus (2015) and Aakre (2013). Herbicide cost, in maize and soybean were fixed at $ 54.34 ha^{-1}, and cost of insecticide in soybean was fixed at $ 17.29 ha^{-1}, according to Swenson and Haugen (2014). In maize, two applications of herbicide were assumed, using a surface sprayer (Boom sprayer, self-propelled, 20.4 m). Similarly, in soybean two applications of herbicide were considered and in addition, a single application of insecticide for soybean aphid (*Aphis glycines* Matsumura) control was considered. Harvesting was done using a combine harvester (rigid platform, 6.1 m) for both maize and soybean. Seed drying and transport costs were not considered in the analysis. For each system, crop insurances cost, machinery repair cost, operating interest, miscellaneous costs, and fixed costs calculated based on Swenson and Haugen (2014), and added together and included as “other costs”.

Economic output was calculated based on (1) grain value at harvest with current prices times the yield (2) value of top soil saved via growing a soil cover (3) value of N that the cover crop was able to uptake and mineralized (4) value of N loading reduction.

The grain price used was $146 and 337.8 Mg^{-1}, for maize and soybean respectively (Swenson and Haugen, 2014). Grain yields were calculated based on the results obtained from the experiment.

For both crops, average yield of the plots with no camelina (check plots) was considered as the grain yield for monoculture systems. Similarly, the average yield of the plots intersown with winter camelina at the same sowing date as the main crop (SD1) was used to represent camelina-drilled The average yield of the plots intersown with winter camelina at Dates 2 and 3 (SD2 and SD3) was used to represent camelina-broadcast system.

The value of top soil saved from erosion by growing a soil cover was estimated at $11.14 ha^{-1} according to Roth et al. (2016). Assuming 100% mineralization of camelina, the value of mineralized N was calculated by multiplying the price of N times the potential N uptake in camelina biomass in the spring (assuming 100% of camelina cover and 100% of the N in camelina is released and available to the subsequent crop). The highest potential N uptake values obtained in the experiments in camelina were used (59 and 57 kg N ha^{-1}, in maize and soybean, respectively). The value of N that is prevented from leaching was calculated by multiplying the price of N, times the amount of N that is prevented from loading due to the cover crop, which is assumed as 14.8 kg N ha^{-1} (Roth et al., 2016). The net revenue from a system was estimated as the difference between the total revenue and the total production cost. A sensitivity analysis was performed to validate the results obtained. This analysis considered a 10% fluctuation in the price of grain and yield potential, and calculated profit fluctuations for each of those scenarios.

Table 4.1. Actual and simulated input costs used for the economic analysis of different cropping systems containing maize and soybean monoculture, camelina drilled at the same time as maize and soybean, and camelina broadcast within maize and soybean, across four environments at Fargo, and Prosper, ND and Morris, MN in 2014 and 2015.

Input	Number of units	Price per unit ($)
Diesel	1 L	0.97
Fertilizer	kg ha^{-1}	
N (urea)	150 N	1.02
P (Monoammonium phosphate)	40 P_2O_5	0.96
K (KCl)	30 K_2O	0.86
Seed		
Maize	40	8.42
Soybean	74.6	2.29
Camelina	10	4.45
Chemicals	ha^{-1}	
Herbicide	1	54.34
Insecticide	1	17.29
Machinery		
Field cultivator (18.3 m)	1	13.04
Row crop planter (24 row, 18.3 m)	1	41.37
Presswheel drill (9.1 m)	1	33.36
Aerial sowing	1	20.96
Chemical application (Boom sprayer, 20.4 m)	1	8.62
Combine (Rigid platform, 6.1 m)	1	81.98

4.3.4. Statistical Analysis

Statistical analysis was conducted using standard procedures for a randomized complete-block design with a split-plot arrangement. Each location-year combination was defined as an “environment” and considered a random effect in the statistical analysis. The different cropping systems were considered fixed effects. Means separation was performed *F*-protected LSD comparisons at the $P \leq 0.05$ probability level. Analysis of variance and mean comparisons were conducted using the Mixed Procedure of SAS (SAS Institute Inc., 2014). Trait error mean squares were compared for homogeneity among environments according to the folded *F*-test and if homogeneous, then a combined ANOVA was performed across environments. Treatment means separation was determined by *F*-protected LSD comparisons at the $P \leq 0.05$ probability level. Simple correlation analysis between CP, ADF, NDF with biomass yield was done for the camelina spring regrowth in soybean.

4.4. Results and Discussion

4.4.1. Climatic and Soil Characteristics

The 2014-2015 seasonal temperatures were very close to normal from May 2014 to April 2015 for Fargo, Morris, and May 2015 to April 2016 for Prosper and Morris (Fig. 4.1a, 1b, 1c, 1d). Rainfall deficit in Fargo was 52 and 43% in July and August of 2014, respectively. The lack of snow cover during the 2014-2015 increased winter-kill of overwintering crops. In Prosper, during 2015, rainfall deficit was 47, 67, and 50% for the months of August, September, and October, respectively. Lack of snow fall from November 2015 through March 2016 was also observed at this location. In Morris, a rainfall deficit of 66, 77, and 85% was observed in July, September, and October of 2014, respectively and 63, 55, and 38% in June, September, and October of 2015, respectively. However in May 2015, both Prosper and Morris observed an excessive amount of rainfall which was more than 100% compared its normal amount for that month.

Soil tests indicated that the Morris site had generally lower fertility than Fargo and was somewhat similar to Prosper for N and P but lower in K (Table 4.2). All sites were fertilized according to the soil test. Thus, nutrient deficiency was not a factor in the experiment.

4.4.2. Maize Grain, and Biomass Yield, and Plant Height

The combined analysis of variance across environments for maize grain and biomass yield, plant height, ADF, NDF, IVDMD, TDN, and N uptake showed differences ($P<0.05$) for the sowing date main effect (Table 4.3). The mean plant height of maize was significantly lower, only when camelina was intersown at the same date as maize (Table 4.4). These results indicate camelina apparently does not significantly compete with maize when sown after V4-V5 stage at both row spacings. Biomass yield also was reduced only when camelina was sown at the same time as maize, but no interaction with row spacing was observed (Table 4.3).

The interaction of row spacing and sowing date was significant only for grain yield (Table 4.3). Maize grain yield was reduced only when camelina was intersown at the same date as maize in the 61-cm row spacing (Fig. 4.2). Seed yield reduction was 13.6% averaged across both row spacings and 16.7% for the 61-cm row spacing. Grain yield was greater when sown at 61-cm for all sowing dates, except when camelina was intersown at the maize ‘silking’ stage at the 76-cm row spacing. Studies on competition between weeds and maize indicate that the critical period for weed control in maize ranges from V1 to V12 stages to prevent grain yield losses of more than 5% (Tursun et al., 2016) or V4 toV10 to prevent economic losses (Keller et al., 2014). However, maize plants detect the presence of another growing plant nearby at very early growth stages, which prompts them to modify their shoot/root ratio, cell wall composition, growth, and development (Liu et al., 2009, 2016). Maize seedlings can respond to the presence of weeds within 24 h after emergence of the weeds resulting in reduced seedling growth and development (Page et al., 2009). This early detection of the presence of a foreign plant by maize, might be of importance for managing the intersowing of cover crops such as winter camelina into maize-soybean cropping systems.

Table 4.2. Soil test results from the experimental sites at Fargo, Prosper, ND, and Morris, MN, in 2014 and 2015.

Environment	N- NO_3 (0-15 cm-depth)	N-NO_3 (15-60 cm-depth)	P	K	OM	pH
	-----------------kg ha^{-1}	----------------	--mg kg^{-1}--		g kg^{-1}	
Fargo 2014	36.6	70.0	10.1	406	75.0	7.9
Morris 2014	10.3	39.1	4.7	128	47.0	8.1
Morris 2015	14.0	51.0	9.3	165	45.0	8.1
Prosper 2015	12.7	30.3	4.2	345	38.7	6.7

OM=Organic matter.

4.4.3. Camelina Soil Cover in Maize

Camelina soil cover in the fall and spring was low and not significant among treatments (Table 4.5). Most camelina seeds sown the same date as maize emerged, but this was only a visual observation, unfortunately stand counts were not taken at emergence. Apparently, many plants died after emergence likely by competition or soil water deficit (not measured). Lack of rainfall observed in all locations in the months of July and August, and the lack of snow cover, especially during 214-2015 may have contributed to the low camelina stand (Fig 4.1). Camelina maize harvest providing little soil cover. The highest soil cover present in the fall averaged across four environments was when camelina was sown at silking stage of maize, although not significant from the other treatments due to the high variability among treatments (Table 4.5). All surviving camelina plants stayed in rosette stage, none of them bolted until next spring.

In the spring, highest camelina cover and survival was for those sown after maize harvest (Table 4.5). Camelina was broadcasted on SD2-SD4 which limited the emergence on dates with rainfall deficit in the weeks after sowing. The rainfall deficit observed in July and September of 2014 and June of 2015 in Morris was likely the main factor of poor establishment of camelina in SD2 and SD3, but without stand counts at emergence, this could not be confirmed. Seeds were broadcasted 23 June and 29 July in 2014 and 22 June and 28 July in 2015 in Morris. Rain deficit was observed in the months following SD2 and SD4, but not in the months following SD3. Lack of snow cover from November to March could have also reduced camelina stands. Camelina sown after maize were very small going into the winter to record significant coverage, but were able to survive providing coverage early in the spring.

4.4.4. Maize Biomass Composition

Although there was no maize yield reduction observed when sowing camelina after the V4-V5 stage, there were differences detected in NDF, ADF, IVDMD, and TDN of maize biomass among some of the intercropped sowing dates compared with the check plants (Table 4.5). Both NDF and ADF were significantly higher in maize plants where camelina was sown at the V4-V5 stage.

Fiber components characterize the cell wall composition, while NDF is the total cell wall content, ADF includes the lignocellulosic portion of the cell wall. Higher NDF and ADF values are an indication of stronger cell walls. This change in maize cell wall composition could have been a response to the presence of camelina in the inter-row, although SD4 which did not have intersown camelina also had higher ADF and NDF than the check.

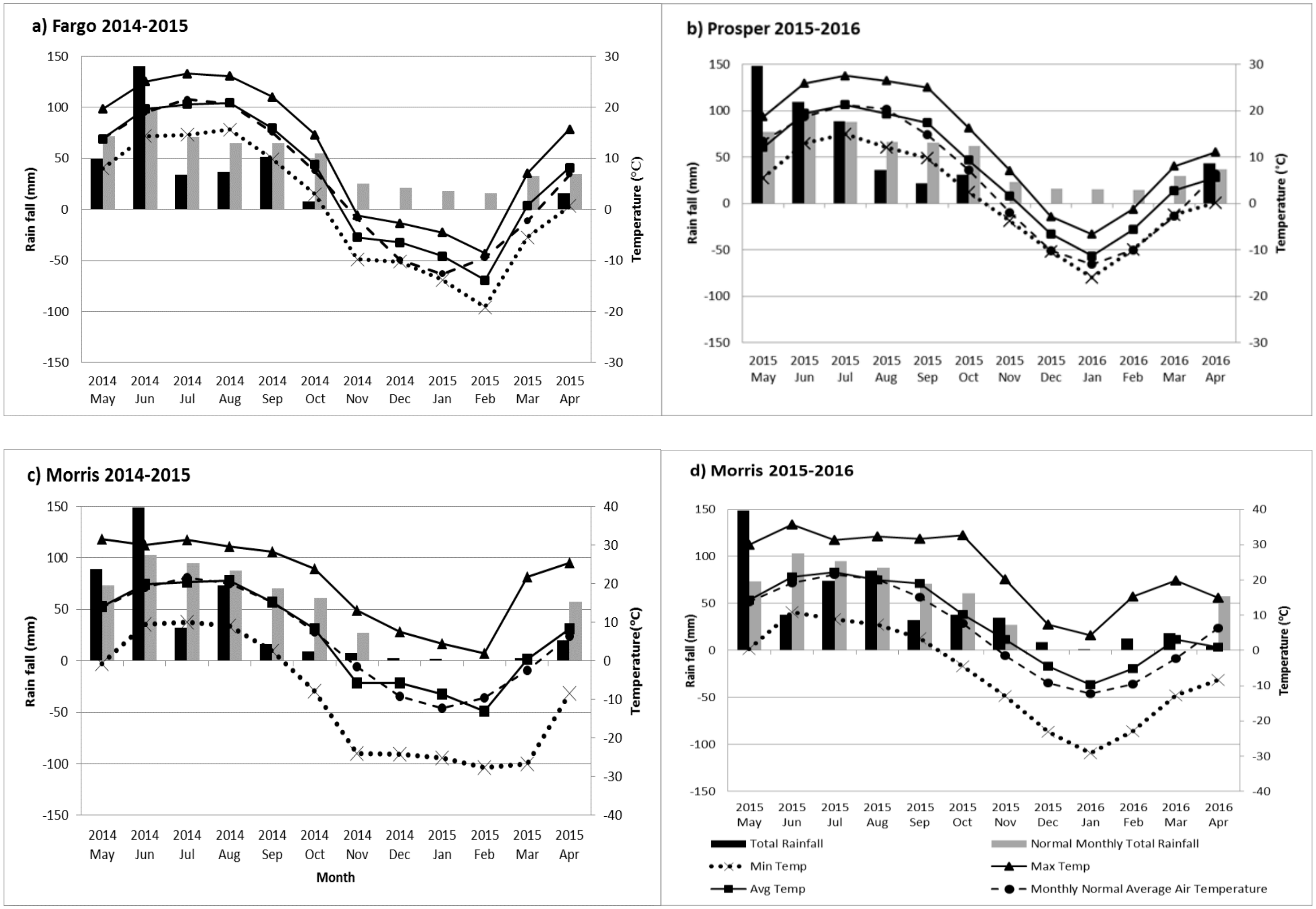

Fig. 4.1. Rainfall, 30-yr average monthly total rainfall, maximum minimum and average temperature, and monthly 30-yr normal average air temperature; a) Fargo, ND 2014-2015, b) Prosper, ND 2015-2016, c) Morris, MN 2014-2015, d) Morris, MN 2015-2016

Table 4.3. Analysis of variance and mean squares for five maize growth stages and two row spacing for plant height, grain yield, biomass yield, crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), starch content, in-vitro dry matter digestibility (IVDMD), total digestible nutrients (TDN), neutral detergent fiber digestibility (NDFD), N content, N uptake of maize, and camelina plant coverage, across four environments (Env), Fargo, and Prosper, ND and Morris, MN in 2014 and 2015.

Source of variation	df	Height ($\times 10^4$)	Grain yield	Biomass yield	CP	ADF	NDF	Starch	IVDMD	TDN	NDFD	N ($\times 10^3$)	N uptake	Camelina coverage
Env	3	-	-	-	-	-	-	-	-	-	-	-	-	-
Rep(env)	8	-	-	-	-	-	-	-	-	-	-	-	-	-
Row space	1	5.6	175.4	116	0.03	1.3	0.04	1.5	0.7	0.5	2.4	0.7	10926	6
Env x row space	3	8.1	80.0	17	0.83	44.3	78.45	77.6	38.9	19.3	74.1	20.9	331	158
Error (a)	8	34.7	4.4	58	0.06	0.2	0.90	0.4	0.3	0.1	1.7	1.4	1092	16
Sowing date	4	69.5**	7.9*	99*	1.06	46.8*	81.56*	61.1	35.1*	20.2*	53.1	28.0	14339*	587
Env x sowing date	12	9.3	2.3	21	0.75	11.8	22.60	20.8	10.0	5.1	25.8	18.7	2959	177
Row space x sowing date	4	19.1	2.4*	34	0.33	6.3	8.83	15.9	5.0	2.7	23.7	8.3	1654	26
Env x row space x sowing date	12	16.4	2.4	12	0.89	54.1	97.47	84.6	33.7	23.5	40.6	23.3	2537	90
Error (b)	64	14.6	2.2	14	0.07	0.7	1.78	1.7	0.4	0.3	0.9	1.7	1439	52
CV, %		16780.2	14.1	16	4.04	4.2	3.58	3.3	0.7	0.7	1.5	4060.4	16	141

*, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

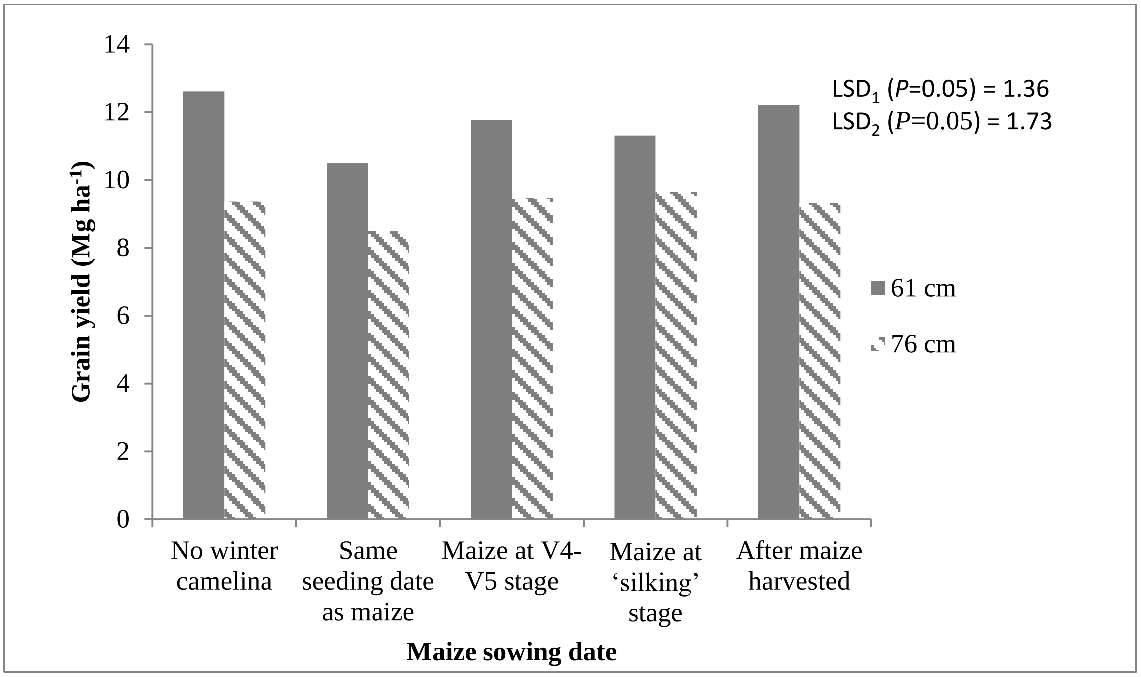

Fig. 4.2. Mean maize seed yield on plots intersown with winter camelina at different maize growth stages, in two row spacings (76 cm and 61 cm) and averaged across four environments at Fargo in 2014, Prosper in 2015 and Morris, MN in 2014 and 2015. LSD_1: To compare the means of different seeding date treatments within a row spacing treatment; LSD_2: To compare the means of the different seeding date treatments across different row spacing).

Table 4.4. Mean plant height of maize, at harvest, when intersown winter camelina for four sowing dates averaged across two row spacing treatments and four environments at Fargo in 2014, Prosper in 2015, and Morris, MN in 2014 and 2015.

Camelina sowing date	Plant height
	m
Check	2.29
Same sowing date as maize	2.24
Maize at V4-V5 stage	2.28
Maize at ‘silking’ stage	2.28
After maize harvested	2.28
LSD (*P*=0.05)	0.02

Evidence for cell wall composition changes in plants, with and without competition has been reported by Liu et al., (2009, 2016) and Page et al., (2009). Higher NDF and ADF usually results in lower TDN and IVDMD and this was the response observed between check plants and those with camelina intersown at the V4-V5 stage. In maize harvested for grain, a change in the biomass composition is not of significance, however in silage maize, a reduction in forage quality would impact animal performance.

4.4.5. Maize Nitrogen Uptake

Nitrogen uptake in maize plants was significantly reduced only when camelina was sown at the same time as maize, following the same response as for biomass yield (Table 4.5). Although camelina has been classified as of low competitive ability (Davis et al., 2013), the results suggest camelina competed for soil NO_3-N with maize early in the season. This was expected because other researchers have reported that most of the N uptake in maize occurs early in the season before 1000 growing degree days (Ciampitti et al., 2013) at the same time camelina

N uptake likely occurred. Maize plants deplete soil NO_3-N mainly between V3 and V15 growth stage whether weeds are present or not and with N fertilization rates between 0 to 120 kg N ha^{-1} (Jalali et al., 2012). Furthermore, (Gambin et al., 2008) stated, grain development during the grain filling period is influenced by accumulation and allocation of N to the developing ear, and any shortage could lead to decreased grain weight.

4.4.6. Soybean Seed and Biomass Yield

The combined analysis of variance across environments for soybean plant population, plant height, grain yield, protein, oil content, and percent camelina plant coverage, showed differences (P<0.05) in grain yield for camelina sowing date, and environment by row space interaction for soybean grain yield and protein content only (Table 4.6).

Table 4.5. Mean maize biomass yield, camelina fall and spring soil cover, ADF, NDF, IVDMD, TDN, and N uptake of maize at harvest, for four sowing dates averaged across two row spacing treatments and four environments at Fargo in 2014, Prosper in 2015, and Morris, MN in 2014 and 2015.

	Maize	Camelina		Maize biomass				
Camelina sowing date	Biomass yield	Fall cover†	Spring cover†	ADF‡	NDF	IVDMD	TDN	N uptake
	Mg ha^{-1}	%	%	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	kg N ha^{-1}
Check	25.1	-	-	177	354	866	752	268
Same sowing date as maize	20.1	9.8	6.7	188	366	866	745	204
Maize at V4-V5 stage	23.4	8.8	10.0	207	392	848	732	236
Maize at 'silking' stage	24.9	16.9	8.8	181	359	870	750	255
After maize harvested	24.3	14.0	13.3	206	392	844	733	249
LSD (*P*=0.05)	4.7	NS	NS	21	30	20	14	34
N	120	47	21	120	120	120	120	120

†Spring and fall cover analysis was conducted only with plots with camelina plants. Fall cover means were averaged from samples from Fargo and Morris in 2014 and Prosper and Morris in 2015 *n*=47. Sampling dates for camelina fall cover: 22 October 2014 in Fargo, 20 October 2014 in Morris, 20 October 2015 in Prosper and 29 September 2015 in Morris. Spring cover means include samples from Morris in 2015 and 2016, sampling dates 5 May 2015 and 25 April 2016 (*n*=21).

‡Quality parameters: total digestible nutrients (TDN), acid detergent fiber (ADF), neutral detergent fiber (NDF), and in vitro dry matter digestibility (IVDMD).

Similar to maize, soybean seed yield averaged across row spacings and environments was reduced only when camelina was sown at the same time as soybean (Fig. 4.3). The row spacing main effect and the interaction between row spacing and sowing date were not significant. Yield reduction was 9.5% of the soybean-check treatment without relayed camelina. The low competitive ability of camelina was probably the reason that even when camelina was sown at the same time as soybean, yield loss was less than 10%. This indicates that camelina's low competitiveness gives it good potential as a cover crop for intersowing into standing soybean. Alternatively, it is also possible that soybean has a better competitive ability than maize in intercropping with camelina. A similar response was observed by Berti et al. (2015), in relay cropping of maize and soybean into standing camelina. Winter camelina stayed in the rosette stage under the soybean canopy thus limiting the risk of foreign green material at harvest, as green material may impact the seed color, thus its quality by staining the seeds during harvesting operations (Dr. H. Kandel, personal communication, 2015).

Yield losses reported in other crops intercropped with camelina vary from 0 to 25%. Dry pea seed yield in mixture with camelina was not significantly different than dry pea as a sole crop (Saucke and Ackermann, 2006). While 25% yield loss in faba bean (*Vicia faba* L.) intercropped with camelina was reported by Ghaouti et al., (2016). Other authors have reported 27 to 38% reduction in soybean seed yield in maize-soybean intercropping when both crops were sown and harvested at the same time (Liu et al., 2017).

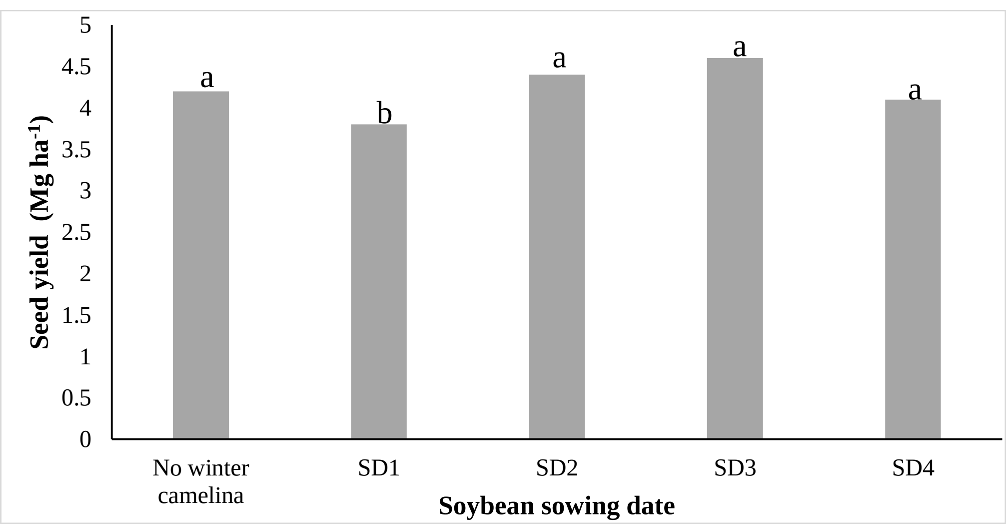

Fig. 4.3. Mean soybean seed averaged across three environments at Prosper in 2015 and Morris, MN in 2014 and 2015 on plots intersown with winter camelina. Date 1 (SD1), at the same sowing date as soybean, Date 2 (SD2) at V3-V4 soybean growth stage, Date 3 (SD3) at R1-R2 soybean stage, and Date 4 (SD4) after soybean harvest. Small case letters indicate significant differences among sowing dates and the check (no winter camelina). Mean separation test LSD, *P*=0.05.

4.4.7. Camelina Spring Biomass Yield, Composition, and Potential N and P Uptake

In the maize experiment, camelina biomass yield, NDF, ADF and potential N and P uptake in spring regrowth were similar for all sowing dates (*P*=0.05) (Table 4.7). Biomass yield fluctuated between 966 and 2240 kg ha^{-1} of aerial biomass (*n*=21).

Potential N uptake varied between 24 and 59 kg N ha^{-1} and potential P uptake ranged between 4.3 and 9.8 kg P ha^{-1}. This N and P uptake represents the potential uptake, assuming a full camelina establishment, and this is not related to the percent coverage shown on Table 4.5. Camelina scavenging ability for soil nutrients falls within the range observed for other Brassicaceae cover crops (Dean and Weil, 2009; Sapkota et al., 2012; Liu et al., 2014, 2015). Brassica cover crops have been studied extensively with the goal to reduce nutrient losses from agriculture to watersheds (Weil and Kremen, 2007). Nitrogen uptake in the fall by brassica cover crops has been reported to fluctuate between 36 to 171 kg N ha^{-1} which is similar to or greater than rye (42 to 112 kg N ha^{-1}) (Dean and Weil, 2009). Although most brassica cover crops do not survive the winter, Dean and Weil (2009) reported a rapeseed spring N uptake of 41 to 118 kg N ha^{-1}. In terms of P uptake, oilseed radish (*Raphanus sativus* var. *oleiformis* L.), white radish (*R. sativus* var. *longipinnatus* L.), and white mustard (*Sinapis alba* L.) have been found to range between 2.0 and 8.0 kg P ha^{-1} in Sweden (Liu et al., 2014, 2015), similar to those in this study. Similarly as observed in maize, the highest values of ADF and NDF in camelina were for plants sown at V4-V5 stage although not significant from the other treatments.

In the soybean experiment, camelina soil cover in the fall averaged across three environments was significant for sowing date (*P*=0.05, *n*=25) (Table 4.8). Camelina sown after soybean harvest had the highest percentage of soil cover at 50%.

Table 4.6. Analysis of variance and mean squares for five soybean growth stages and two row spacing for plant density, plant height, grain yield, protein, oil content, and percent camelina plant coverage per plot, across three environments (Env) at Prosper, ND and Morris, MN in 2014 and 2015.

Sources of variation	df	Plant density ($x10^6$)	Plant height	Grain yield	Protein content	Oil content	Camelina plant coverage
Env	2	-	-	-	-	-	
Rep(env)	6	-	-	-	-	-	
Row space	1	111	0.016	5.72	0.78	0.01	1580
Env x row space	2	114	0.003	13.26***	7.08***	0.24	86
Error (a)	6	2670	0.005	0.36	0.28	0.43	188
Sowing date	4	1173	0.004	1.66*	0.82	0.16	58
Env x sowing date	8	33	0.002	0.17	0.77	0.26	222
Row space x sowing date	4	1536	0.001	0.04	0.74	0.30	1353
Env x row space x sowing date	8	27	0.002	0.07	1.09	0.35	1421
Error (b)	48	2704	0.002	0.44	0.53	0.20	98
CV, %	12.9	13	5.873	15.91	1.88	2.17	118

*, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

Table 4.7. Mean camelina biomass yield, ADF, NDF, potential N and P uptake of camelina sown at four maize growth stages in Morris† in 2015 and 2016.

Sowing growth stage	Biomass yield	ADF	NDF	PNU	PPU
	kg ha^{-1}	g kg^{-1}	g kg^{-1}	kg N ha^{-1}	kg P ha^{-1}
Same sowing date	1112	230	283	24	4.3
Maize at V4-V5 stage	966	309	386	26	4.9
Maize at 'silking' stage	2204	276	336	59	9.8
After maize harvested	2240	264	320	55	9.2
LSD (*P*=0.05)	NS	NS	NS	NS	NS
N	21	11	11	21	21

†Spring and fall cover analysis was conducted only with plots with camelina plants. Biomass yield, potential N uptake (PNU), and potential P uptake (PPU) include samples from Morris in 2015 and 2016, sampling dates 9 May 2015 and 25 April 2016 (*n*=21). ADF and NDF are from Morris 2015 (*n*=11).

This indicates that similar to maize the intersown treatments of camelina were shaded by the soybean crop, resulting in competition that led to reduced area coverage following soybean harvest. Also, SD2 and SD3 stands were likely decreased by the lack of rainfall in the months of July and August. Soil cover in the spring averaged across two environments was significantly higher for camelina sown after soybean (*P*=0.05, *n*=29), following the same trend observed in the fall.

Establishment of broadcasted camelina into standing soybean was influenced by timely rainfall. In this study, the best soil coverage in the fall and spring was provided by camelina sown following soybean harvest. This was probably a combination of both, timely rainfall and lack of competition with soybean. It is clear that surface broadcasting is risky for establishing winter camelina in a standing crop. Fisher et al. (2011) reported that the establishment of rye by aerial broadcasting depended largely on rainfall after sowing.

Drilling camelina in the inter-row plot area at the V6 to R4 stages in soybean might be a means to increase its establishment and provide soil protection in the fall after soybean harvest when erosion potential increases. However, additional research on sowing dates and methods to enhance camelina survival prior to soybean harvested is needed.

The camelina spring regrowth averaged across two environments was similar in biomass yield, and potential N and P uptake among sowing dates (P=0.05, n=29) (Table 4.8). Camelina biomass yield, and potential N and P uptake in the spring varied between 360 and 2097 kg ha^{-1}, 14 and 57 kg N ha^{-1}, and 1.5 and 6.9 kg P ha^{-1}, respectively. Spring potential N and P uptake of camelina after soybean were similar to those observed in camelina after maize, indicating the main crop does not affect the ability of camelina to take up soil nutrients in the spring. Nutrient uptake values are within the ranges reported by other researchers (Dean and Weil, 2009; Liu et al., 2014). The nutrient scavenging ability of winter camelina in the spring is likely greater than in the fall, because plant growth and biomass accumulation is greater in the spring due to higher nutrient requirements for life cycle completion associated with transitioning from vegetative to reproductive development. Fall potential N and P uptake was not evaluated in this study. A winter-hardy crop like camelina has potential to decrease NO_3-N leaching and P run-off and thus improve water quality (Ott et al., 2015). Crude protein, NDF, and ADF in camelina biomass sampled in the spring, average of two environments, were different among sowing dates. Crude protein was highest in camelina intersown at V3-V4 stage, and ADF and NDF were highest in camelina sown following soybean harvest (Table 4.8). Higher NDF and ADF was observed in the treatments with highest average camelina biomass yield. Larger plants usually have lower CP and higher ADF and NDF. A negative correlation (r=-0.93) was observed between biomass yield and CP. This is likely due to a dilution effect (Bastidas et al., 2008). Conversely, both ADF and NDF had a positive correlation with biomass yield r=0.99 and r=0.95, respectively.

4.4.8. Soybean Oil and Protein Content

Soybean seed oil and protein content were not significantly different for row spacing, sowing date or their interaction (Table 4.6). This indicates that even a significant effect on seed yield was observed when camelina was sown at the same time in maize or soybean, it did not affect the seed composition (data not shown).

4.4.9. Economic analysis

When comparing the net return of maize monoculture with maize intersown with camelina, as expected the latter systems had the lower net returns (Table 4.9). Extra seed cost and planting cost associated with the sowing of camelina increased the production cost, compared with the maize monoculture. The total revenue of maize with camelina-broadcast system was slightly higher compared with maize monoculture due to the extra revenue generated by the cover crop. The extra revenue generated by the cover crop which is $ 87.5, can offset the sowing costs associated with camelina $ 77.8 and 65.5 for drilled and broadcasted systems, respectively. When comparing the two systems that include camelina, maize with camelina drilled at the same time, has a negative net return, compared with a positive net return when camelina was broadcasted into maize. This is mainly due to the lower grain yield reported in the maize camelina-drilled system.

Table 4.8. Mean camelina fall and spring cover, spring biomass yield, potential N uptake (PNU), potential P uptake (PPU), CP, NDF, and ADF sown at different growth stages of soybean in two environments, Morris in 2015 and 2016†.

Sowing date	Fall cover†	Spring cover†	Biomass yield	PNU	PPU	CP	ADF	NDF
	%	%	kg ha^{-1}	kg N ha^{-1}	kg P ha^{-1}	-----------g kg^{-1}------------		
Same as soybean	24.1	21.7	1607	49	6.9	192	329	392
Soybean at V3-V4 stage	5.0	7.5	360	14	1.5	236	285	381
Soybean at R1-R2 stage	20.0	11.7	1687	57	6.0	210	338	433
After soybean harvested	50.0	60.8	2097	56	6.0	168	413	480
LSD (*P*=0.05)	24.0	22.4	NS	NS	NS	19	44	26
N	25	29	29	29	29	15	15	15

† Spring and fall cover analysis was conducted only with plots with camelina plants. Fall cover includes samples from Morris in 2014 and Prosper and Morris in 2015, *n*=25. Sampling dates for camelina fall cover: 20 October 2014 in Morris, 20 October 2015 in Prosper, and 29 September 2015 in Morris. Spring cover , biomass yield, PNU, and PPU include samples from Morris in 2015 and 2016, sampling dates 9 May 2015 and 25 April 2016 (*n*=29). CP, ADF, and NDF are from Morris 2016 sampling (*n*=15).

An expected 10% increase in maize grain price would be sufficient in changing the net revenue of the maize camelina-drilled system form a negative value to a positive value (Table 4.10). However, the improved net return from grain price increase is only sufficient in adding a profit of \$ 138 ha^{-1}. This low return may not be sufficient to attract growers to practice this system when considering much higher net returns of \$ 364 and 319 ha^{-1} from maize monoculture and maize camelina-broadcasted systems. Furthermore, if grain prices decrease 10% from the current price, that will resulted in a break-even net return for the maize with camelina-broadcasted system. In that kind of a situation, it would be hard to convince growers to grow a cover crop such as camelina, unless there are ways to evaluate and add a value for other ecosystem services performed by the cover crop, which will increase the net return at least to a level similar to that of maize monoculture.

In contrast to maize, when comparing the net returns of soybean monoculture with soybean grown with camelina, as expected soybean camelina-broadcast system has the highest net return (Table 4.11). This is mainly due to the increased revenue from grain and from the extra revenue generated from having the cover crop. Also in contrast to maize, system with soybean with camelina-drilled does not resulted in a negative net return. As expected, the two systems with camelina differ in net return of approximately \$ 215 ha^{-1} due to the lower soybean yield associated with the soybean camelina-drilled system.

An unexpected 10% decrease in soybean grain price would not result in negative net return in any system, even at a 10% decrease in yield (Table 4.12). Since net return of soybean monoculture system is similar to that of soybean with camelina-broadcasted system, it would be much more appealing to growers to employ a cover crop such as camelina in to their existing soybean monoculture systems, than in the case of maize.

In a double and relay cropping study done by Gesch et al. (2014), also reported higher production costs and net losses associated with double and relay cropping camelina with soybean, compared with soybean monocrop.

Table 4.9. Economic analysis of three different systems: maize monoculture maize with camelina drilled at the same time as maize, and maize with camelina intersown by broadcasting across four environments at Fargo, and Prosper, ND and Morris, MN in 2014 and 2015.

Variable	Maize monoculture	Maize with camelina drilled	Maize with camelina broadcasted
Inputs	$ ha^{-1}	$ ha^{-1}	$ ha^{-1}
Land preparation			
Field cultivator	13.0	13.0	13.0
Seeding			
Row crop planter	41.4	37.2	37.2
Small grain drill		33.3	
Aerial sowing			21.0
Maize seed	340.2	340.2	340.2
Camelina seed		44.5	44.5
Fertilization			
Application-broadcast	15.2	15.2	15.2
N	155.3	155.3	155.3
P	40.5	40.5	40.5
K	25.7	25.7	25.7
Chemicals			
Spraying	17.2	17.2	17.2
Herbicide	54.3	54.3	54.3
Harvesting			
Combine	82.0	82.0	82.0
Other costs	633.1	633.1	633.1
Total production cost	1417.8	1491.5	1479.2
Outputs			
Grain	1603.7	1387.5	1539.4
Value for preventing soil loss		11.1	11.1
Mineralized N		61.1	61.1
N loading reduction		15.3	15.3
Total revenue	1603.7	1475.1	1627.0
Net return	185.9	-16.5	147.8

However, contrast to this study where camelina was interseeded in to soybean to serve as a cover crop, Gesch et al. (2014), considered camelina as a second cash crop and calculated a value for camelina seed yield. This also highlight the fact that grower acceptance to these novel systems depend on the net return from the cash crop and estimating a value for ecosystem services performed by the cover crop.

Table 4.10. Sensitivity analysis for net return of maize produced from three different systems containing maize monoculture, camelina drilled at the same time as maize, and camelina broadcast within maize.

	Maize yield (Mg ha^{-1})								
	Maize			Maize-camelina drilled			Maize-camelina broadcasted		
Price $ Mg^{-1}	12.1	11.0	9.9	10.5	9.5	8.6	11.6	10.5	9.5
	$ ha^{-1}								
162	542	364	186	292	138	-16	490	319	148
146	346	186	26	122	-16	-155	302	148	-6
133	186	40	-106	-16	-143	-284	148	8	-132

4.5. Conclusions

Broadcast establishment of winter camelina into standing maize and soybean greatly depended on rainfall after sowing. Camelina sown on the same date as maize or soybean resulted in lower grain and biomass yield of both crops indicating that camelina intersowing should be done after V3-V5 stages to avoid competition. Camelina establishment and survival in the fall and following spring was better when sown after maize and soybean harvest. Camelina establishment, survival and soil cover was much higher in soybean than in maize, which was likely due to soybean being a less aggressive competitor for light and moisture than maize. With current grain prices, camelina broadcast seeding into soybean have a better chance of grower acceptance than compared to maize, from an economic point of view. In general, winter camelina scavenging ability is within the range reported in other cover crops. Although in the present study, camelina did not provide much soil cover in the fall, when intersown into standing maize or soybean, its ability to survive the winter and scavenge nutrients in the fall and spring gives this crop good potential to be integrated as a cover crop in maize-soybean systems in the US Midwest.

Table 4.11. Economic analysis of three different systems containing soybean monoculture, camelina drilled at the same time as soybean, and camelina broadcast within soybean across four environments at Fargo, and Prosper, ND and Morris, MN in 2014 and 2015.

Variable	Soybean monoculture	Soybean with camelina drilled	Soybean with camelina broadcasted
Input	$ ha^{-1}	$ ha^{-1}	$ ha^{-1}
Land preparation			
Field cultivator	13.0	13.0	13.0
Seeding			
Row crop planter	41.4	37.2	37.2
Small grain seeder		33.3	
Air seeding			21.0
Soybean seed (treated and with inoculant)	171.0	171.0	171.0
Camelina seed		44.5	44.5
Fertilization			
Application-broadcast	15.2	15.2	15.2
P	38.7	38.7	38.7
K	25.7	25.7	25.7
Chemicals			
Spraying	25.9	25.9	25.9
Glyphosate	54.3	54.3	54.3
Insecticide	17.3	17.3	17.3
Harvesting			
Combine	82.0	82.0	82.0
Other costs	491.8	491.8	491.8
Total production cost	976.2	1050.0	1037.6
Outputs			
Grain	1418.7	1283.6	1486.2
Value for preventing soil loss		11.1	11.1
Mineralized N		57.7	57.7
N loading reduction		15.0	15.0
Total revenue	1418.7	1367.4	1570.1
Net return	442.4	317.4	532.4

Table 4.12. Sensitivity analysis for net return of maize produced from three different systems containing soybean monoculture, camelina drilled at the same time as soybean, and camelina broadcast within soybean.

	Soybean yield (Mg ha^{-1})								
	Soybean			Soybean- camelina drilled			Soybean-camelina broadcasted		
Price $ Mg^{-1}	4.6	4.2	3.8	4.2	3.8	3.4	4.8	4.4	4.0
	$ ha^{-1}								
375	758	600	442	603	460	317	863	698	532
338	584	442	301	446	317	189	681	532	384
307	442	313	184	317	201	69	532	397	262

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CHAPTER 5. ENVIRONMENTAL IMPACT OF NOVEL CROPPING SYSTEMS IN THE NORTHERN GREAT PLAINS OF USA

5.1. Abstract

Intensifying cropping systems by conventional or temporal intensification or a combination of both can improve land productivity while improving sustainability of cropping systems. High input agriculture has led to negative environmental impact either on- or off-site. High fertilizer use has led to land, water, and air degradation by leaching, eutrophication, and greenhouse gas emissions. Inclusion of late-season and/or intersown cover crops, and intercropping have the potential to extend the growing period, reduce environmental impacts, while improving intensification of the cropping system, compared to a conventional monocrop rotations. The objective of this study was to assess environmental impacts of eleven cropping systems involving late-season cover crops, intercropping, intersowing cover crops into standing cash crops, and comparing the impact of those, with conventional monocrop rotations in the North Central US. The system boundary was considered as cradle to the farm gate. Each system scenarios included inputs and associated processes needed to produce seed or biomass at the farm gate and the direct and indirect emissions produced by those inputs and processes. The functional unit considered for the evaluation was ha^{-1} yr^{-1}. Impact assessment was done using the CLM–IA-baseline V3.02/World 1995 method. The environmental aspects evaluated included global warming potential (GWP), abiotic depletion, acidification, eutrophication, ecotoxicity, and human toxicity. Additionally, primary aboveground productivity, the main provisioning ecosystem service of agriculture was estimated. Global warming potential results indicate systems that had maize (*Zea mays* L.), regardless of the end product (either grain or silage) had the highest GWP values compared to other systems, except for the maize-forage sorghum

[*Sorghum bicolor* (L.) Moench] intercrop system. The GWP values range from 1008 to 1043 kg CO_2eq ha^{-1}. Intercropping maize with forage sorghum has the potential to provide comparable or better results, providing biomass with lower environmental impact, compared with maize monoculture. Intersowing of winter camelina [*Camelina sativa* (L.) Crantz.] in to maize or soybean [*Glycine max* (L.) Merr.], did not improve environmental impacts that was considered, mainly due to the additional inputs and processes required, compared with that of the monocrop. Systems that had cover crops also needed additional seeds, sowing, and crop protection applications, thus resulting in additional CO_2 emissions, even with lower N inputs. Although potential benefits might not offset short term GWP, the incorporation of winter hardy and, or cover crop such as camelina, will likely have long-term benefits to the soil health and biodiversity, in the US Midwest.

Keywords: sustainability, intercropping, late season cover crops, intersowing, environmental impact assessment, global warming potential

5.2. Introduction

World population is estimated to increase from 6 billion people in 2000 to 8 billion in 2025 to around 9.2 billion by the year 2050 (Khush, 2005; UNFPA, 2007). During the past five decades the amount of arable land devoted to food production increased by 9% while the food production has more than doubled (Godfray et al., 2010). Competition with other land uses such as urban and infrastructure development, and forest conservation, will hinder bringing new land into crop production (Evans, 2009). Additionally, productive agricultural land has been lost to desertification, salinization, soil erosion, and other consequences of unsustainable land management (Nellemann et al., 2009). In order to face the challenge of feeding increasing world population and to fulfill other land use needs, the productivity and labor utilization per unit area of currently available land needs to be increased (Heaton et al., 2013). Several intensification strategies can be used to improve land productivity. Conventional intensification usually is achieved by advanced genetics and technology, increased inputs and infrastructure targeting yield-limiting traits, while temporal intensification is defined as increasing the number of crops grown in a given period of time.

Intensifying cropping systems by conventional or temporal intensification or a combination of both can improve land productivity while improving sustainability of current cropping systems. A cropping system is the combination of crops grown on a given area within a given time period (Seran and Brintha, 2010). Throughout the world, different cropping systems can be found depending on the local climate, soil, economic factors, and social aspects (Seran and Brintha, 2010). Inclusion of cover crops, double-crops, relay-crops, and intercropping have the potential to extend the crop's growing period, thus improving intensification (Heaton et al., 2013).

Intercropping can be described as, the growing of two or more crops simultaneously on a single field for all or part of their growth cycle in a season (Gallagher, 2009; Machado, 2009). Intercropping improves the diversity, stability, and resilience of the system compared with monocultures grown in the same area (Lin, 2011; Gaudin et al., 2015). Intercropping systems can provide more competition against weeds, act as a barrier against the spread of pests and diseases, prevent soil erosion, act as wind-barrier to prevent wind erosion, and excessive soil water evaporation (Seran and Brintha, 2010). Intercropping can improve the plant nutrient uptake (Li et al., 2003) and may serve as a strategy to reduce N leaching (Stoltz and Nadeau, 2014).

Cover crops can be defined as non-cash crops that are grown with or after a cash crop (Bich et al., 2014). Cover crops have become a viable option for sustainable agriculture because of their contribution to the environment, soil fertility, and improved crop performance (Bich et al., 2014; Gaudin et al., 2015; Ketterings et al., 2015). Because of their inherent symbiotic ability, leguminous cover crops can fix atmospheric N_2 reducing the use of N fertilizer and production costs. Non-leguminous cover crops in the Brassicaceae family are known for their potential to scavenge nitrates from the soil profile and then cycled by plants and soil microbes (McSwiney et al., 2010). Cover crops also provide a range of additional benefits to a cropping system such as increasing soil organic matter (Zhang et al., 2007), water holding capacity, and soil permeability (Carter, 2002), help alleviate soil compaction, which improves water infiltration (Newman et al., 2007), suppress weeds (Brust et al., 2014), and improve P availability and uptake (Sundermeier, 2008).

In the US Midwest, 60% of maize acreage is in rotation with soybean and 25% in continuous maize (Osteen et al., 2012). Less diverse crop rotations are a result of: 1) highly mechanized agriculture, 2) US government farm subsidies, 3) 2007 US legislative mandate to blend maize-based grain ethanol into gasoline, 4) incentives to increase maize presence in crop rotations, and 5) crop insurance subsidies that reduce farmer incentives to manage risk through crop diversity (Robertson et al., 2014). In 2011, 94% of soybean and 70% of maize production area in US, used herbicide-resistant cultivars (Osteen et al., 2012). Reduced plant diversity can have negative effects on many taxa such as arthropods, vertebrates, microbes, and other soil organisms. The loss of these taxa can have important effects on community structure and dynamics such as species extinctions and changes in trophic structure (Zhang et al., 2007). Continuous monocultures yield decreases overtime even with increased external inputs. Yield reduction overtime is attributed mainly to the loss of beneficial soil microbes and macrofauna (Zhang et al., 2007; Bennett et al. 2012). High input agriculture also has led to negative environmental impact either on- or off-site. High fertilizer use has led to land, water, and air degradation by leaching, eutrophication, and greenhouse gas (GHG) emissions (Vitousek et al., 2009). Ideally, fertilizers and soil biota should be managed to deliver nutrients to crops synchronously with demand, but unfortunately most fertilizer applications are done before crop demand, increasing the risk of leaching and run-off (Gregory and George, 2011).

The northern Great Plains of the USA (NGP) comprises mainly the states of North Dakota, Minnesota, South Dakota and northern Iowa, considered the most important food crops producing area in the USA. Agricultural production in the NGP has changed in the last two decades mainly to higher prices and available early-maturing cultivars (Wolfram and Michael, 2009; Weise, 2013). Crops such as wheat (*Triticum aestivum* L.), soybean, maize, canola (*Brassica napus* L.) and other cool-season cereals are common in crop rotations in the NGP, with wheat and canola distributed mainly in the northwestern portion of the NGP and maize and soybean in the southeastern part (Hudson, 2011). Maize and soybean production areas have been expanding North and West in the Corn Belt region due to a longer season, warmer temperatures (Wolfram and Michael, 2009), higher prices between 2009 and 2013, and the development of new early-maturing cultivars adapted to grow in northern areas (Weise, 2013). Currently, the most common cropping system in the southeastern part of the NGP is soybean-maize (NASS, 2014). Higher commodity prices from 2009 to 2013 led farmers to turn marginal and conservation reserve program (CRP) land into annual cropping systems with detrimental consequences to wildlife, water quality, and global warming (Langpap and Wu, 2011). The intensification of row crops has caused a dramatic reduction in crop biodiversity (Aguilar et al., 2015), increase of GHG emissions, nutrient leaching and run-off (Robertson et al., 2014), water shortages due to over extraction (Evans, 2009), soil degradation (Zhang et al., 2007), and the disruption of other ecosystem services (Nellemann et al., 2009).

Ecosystem services (ES) are functions provided by the environment that benefit humans and they can be classified as provisioning, regulating, supporting, or cultural services (Millennium ecosystem assessment, 2005). In 1992, De Groot defined ecosystem services as "capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly". Agricultural ecosystems are managed to optimize the provisioning of food, fiber, and fuel, and depend upon a wide variety of supporting and regulating services, such as soil fertility, nutrient and water cycling, soil carbon storage, water and air quality, pest regulation, and support of biodiversity and pollinators. Agriculture also provides cultural services such as recreation and aesthetic value (Zhang et al., 2007; Power, 2010; Schipanski et al., 2014). Agriculture also receives several types of ecosystem disservices (EDS) that can reduce yield, quality or increase production costs, such as herbivory and competition for water, nutrients, and sunlight (Schipanski et al., 2014).

These ES and EDS depend on how agricultural ecosystems are managed at the site, and on the diversity, composition, and functioning of the surrounding landscape. Landscapes that contain diverse habitat types typically are more compatible for beneficial insects and most often resulting in improved biological control of pests (Zhang et al., 2007).

Ecosystem services to agriculture also affect farmland's economic value. The value of agricultural land depends on production costs linked to ES such as soil fertility and depth, suitable climate and limited pest pressure (Roka and Palmquist, 1997). Increasing the diversity in the cropping systems by incorporating cover crops, intercropping, employing perennial grassland in the marginal land areas, switching from annual to perennial systems enhances many ecosystem services in comparison with a maize monoculture or maize-soybean rotation. A 3-year, six-species rotation of maize, soybean, and wheat, with three cover crops in southwest Michigan, produced maize yields comparable to county average, in addition to rotational benefits and other ecosystem services (Smith et al., 2008). Using cover crops on a 3-year soybean-wheat-maize cropping system increased eight out of eleven ecosystem services studied, without decreasing productivity (Schipanski et al., 2014). Improving agroecosystem diversity can improve the cropping systems resiliency to weather shocks increasing the probability of obtaining high maize yields while decreasing vulnerability of maize and soybean yields to weather variations (Gaudin et al., 2015).

Since most cropping systems are valued in terms of grain yield and short-term profitability (Schipanski et al., 2014), if measured in terms of ES offered, current cropping systems may not be providing many benefits to the environment. Several recent studies in cropping systems in the Midwest and eastern US suggest that cropping systems focused primarily on grain yield and profit, may be neglecting ecosystem services (Schipanski et al., 2014; Syswerda and Robertson, 2014; Werling et al., 2014). The growers may also have the perception that any increase in variation in management practices intended to increase biodiversity or ecosystem services will hinder productivity and their short-term profit (Robertson et al., 2014).

Life cycle assessment (LCA) is considered as a methodology for compilation and evaluation of potential environmental impacts of a production system throughout its life cycle (Buratti and Fantozzi, 2010). According to the international organization for standardization (ISO), LCA can be used to analyze the life cycle of a particular product, or an activity quantitatively, from production, through use and on to disposal, and recycling, within a generic framework provided by ISO 14040 and ISO 14044 (Singh et al., 2010; Borrion et al., 2012). The evaluation of the life cycle of a product can then be used to compare two or more, different production processes in terms of use of resources and emissions (Petre et al., 2013). At present, LCA is extensively used for evaluating bioenergy and food production systems (Tidaker et al., 2014). In accordance with the ISO standards, a LCA assessment consists of four major components, namely: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation (Biewinga and Van der Bijl, 1996). In many LCA studies evaluating similar systems, choice of system boundaries and choice of data used in the study varies. Often simplifications are made due to lack of suitable data. Furthermore, capital goods such as machinery and buildings, production and use of pesticides and mineral fertilizers often get excluded from studies involving agricultural products. As a result, final results may not be accurate (Roer et al., 2012).

However, few studies have addressed the environmental impact of cropping systems that are not yet commonly used in the NGP. Therefore, the objective of this study was to assess the environmental impact of systems involving cover crops, intercropping, intersowing cover crops into standing cash crops, and comparing the impact of those, with conventional monocrop rotations in the North Central US.

5.3. Methodology and Assumptions

A total of eleven cropping sequences were grown and evaluated in Fargo, Prosper, Carrington, ND and Morris, MN, between 2010 and 2016. Experimental methods, sowing dates, design, seed yield, and biomass yield were reported in Samarappuli et al., (2014), and in Berti et al., (2017). Mean biomass and seed yields reported in those studies were used in the LCA. The eleven cropping systems scenarios evaluated are described in Table 5.1. Crop residues were assumed to stay in the field, and all systems analyzed were assumed to be on no-till dryland production. Seed drying and storage after harvest was not considered in this study.

The system boundary was considered as cradle (crop planting) to the farm gate (harvesting) (Fig. 5.1). The system included inputs and associated processes needed to produce seed or biomass at the farm gate and the direct and indirect emissions produced by those inputs and processes. All inputs for each scenario of the analysis are included in detail in Table 5.2.

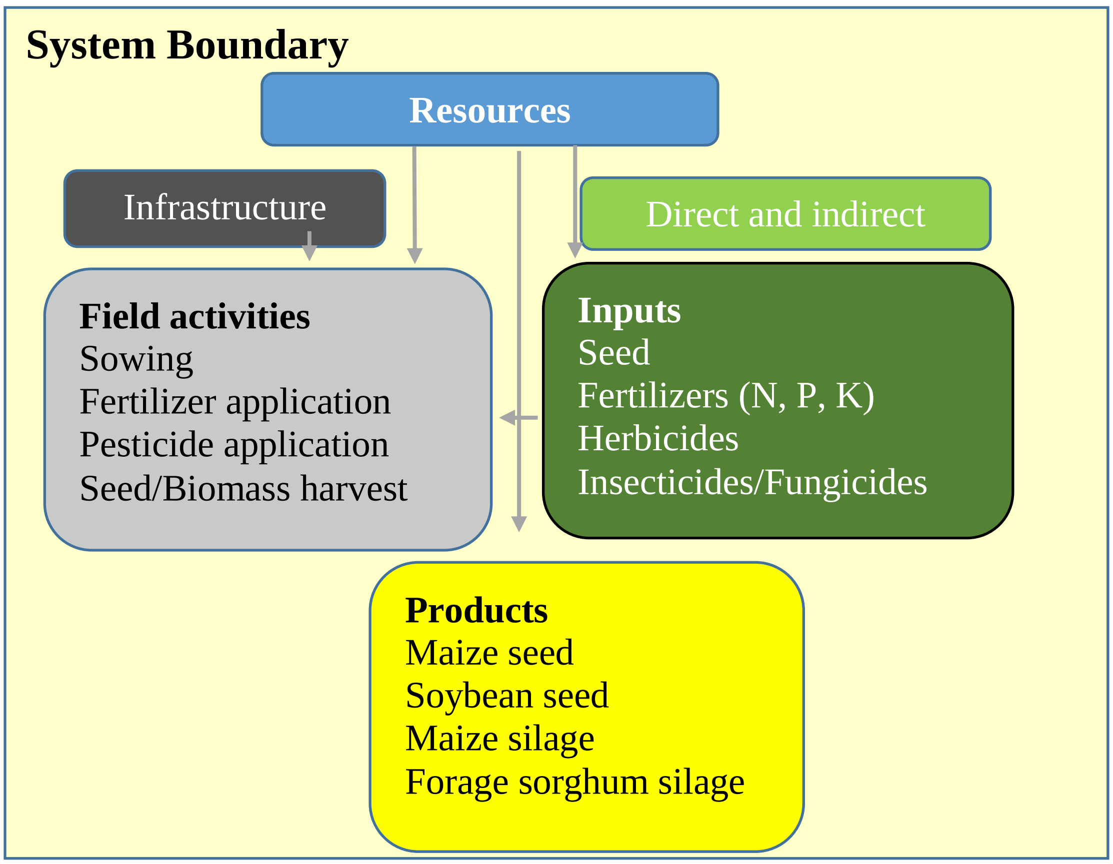

Fig. 5.1. System boundary for the life cycle impact assessment of eleven cropping sequences/systems grown in Minnesota and North Dakota from 2011 to 2016.

Table 5.1. Description of the 11 cropping sequences/systems used in the environmental impact analysis.

Scenario/cropping sequence	Description
Maize monocrop (conventional)-grain (MG)	Maize was sown without a fall cover crop nor intersown with a spring cover crop, and harvested for grain
Maize monocrop (conventional)-silage (MS)	Maize was sown without a fall cover crop nor intersown with a spring cover crop, and harvested for silage
Soybean monocrop (conventional) (SG)	Soybean was sown without a fall cover crop nor intersown with a spring cover crop, and harvested for grain
Forage sorghum (conventional)-silage (FSS)	Forage sorghum was sown without a fall cover crop nor intersown with a spring cover crop, and harvested for silage
Maize-forage sorghum intercrop (MFSS)	Maize was sown with forage sorghum as an intercrop, and harvested for silage
Maize-camelina intersowing (MCG)	Camelina was intersown into maize as a cover crop and maize was harvested for grain
Soybean-camelina intersowing (SCG)	Camelina was intersown into standing soybean and soybean was harvested for grain
Cover crop (legume) in fall- followed by maize in spring (PMS)	Maize was sown after a forage pea fall cover crop, and harvested for silage
Cover crop (non-legume) in fall- followed by maize in spring (RMS)	Maize was sown after a forage radish fall cover crop, and harvested for silage
Cover crop (legume) in fall- followed by sorghum in spring (PFSS)	Forage sorghum was sown after a forage pea fall cover crop, and harvested for silage
Cover crop (non-legume) in fall- followed by sorghum in spring (RFSS)	Forage sorghum was sown after a forage radish fall cover crop, and harvested for silage

The functional unit considered for the evaluation was 1 ha^{-1} yr^{-1}. In dryland environments, LCA by unit of product (seed or biomass) would vary greatly, depending soil water availability and temperature. It is for this, that the LCA was conducted based on 1 ha^{-1} yr^{-1}. This way, the results of the impact analysis would not depend on crop yield, but on inputs.

Table 5.2. Scenarios and inputs for each cropping sequence in the agricultural phase of eleven cropping sequences/systems evaluated in North Dakota and Minnesota in 2011-2016.

Cropping sequence†	N	P	K	Herbicide ‡	Insecticide§	Seed	Diesel⁑
	-----	-----	-----	-----kg ha^{-1}-----	-----	-----	-----
MG	150	40	30	6 + 1.45 + 1.78	0.12	40.0	24.4
MS	80	40	30	6 + 1.45 + 1.78	0.12	30.0	23.9
SG	0	40	30	9 + 0.27	0.03	75.0	24.4
FSS	80	40	30	3 + 1.45 + 1.78	0.12	45.0	23.4
MFSS	80	40	30	3 + 1.45 + 1.78	0.12	37.5	23.4
MCG	150	40	30	6	0.12	50.0	28.7
SCG	0	40	30	6	0.03	85.0	28.7
PMS	50	40	30	9 + 1.45 + 1.78	0.12	107.0	29.3
RMS	50	40	30	9 + 1.45 + 1.78	0.12	44.0	29.3
PFSS	50	40	30	6 + 1.45 + 1.78	0.12	112.0	28.8
RFSS	50	40	30	6 + 1.45 + 1.78	0.12	49.0	28.8

†MG= Maize monocrop (conventional)-grain, MS= Maize monocrop (conventional)-silage, SG= Soybean monocrop (conventional), FSS= Forage sorghum (conventional)-silage, MFSS= Maize-forage sorghum intercrop, MCG= Maize-camelina intersowing, SCG= Soybean-camelina intersowing PMS= Cover crop (legume) in fall- followed by maize in spring, RMS= Cover crop (non-legume), radish, in fall followed by maize in spring, PFSS= Cover crop (legume) in fall followed by forage sorghum in spring, RFSS= Cover crop (non-legume) in fall- followed by forage sorghum in spring.

‡Herbicide: All systems included either one (3), two (6), or three (9) applications of glyphosate at 3 kg a.i.ha^{-1}. Additionally, each system except systems containing soybean or camelina included one application of Bicep II Magnum™ (atrazine + S-metolachlor 1.45 + 1.78 kg a.i. ha^{-1}). System with soybean monocrop (SG) included one application of Select Max™ (clethodim 0.27 kg a.i. ha^{-1}).

§Insecticide: All systems except systems containing soybean, included one application of Capture™ (bifenthrin) at 0.12 kg a.i. ha^{-1}. Systems containing soybean, included one application of Warrior II™ (lambda cyhalothrin) at 0.03 kg a.i. ha^{-1} ⁑Amount of diesel was converted from L ha^{-1} to kg ha^{-1}, considering the density as 0.86 kg L^{-1}

Most growers decide on the inputs to use before the season starts according to the desired yield potential. For example, if in a particular season where rainfall is below normal, thus the crop yield potential might not be achieved, although the inputs remain the same. Therefore it is assumed, the resulting environmental impacts are driven mainly by inputs, rather than yield, during the agricultural phase. However, this is only valid when comparing systems from 'cradle to gate' because processing after the field gate will depend on yield and volume of seed or biomass produced by unit area.

Inputs needed in each scenario were used to calculate the crop's combined LCA's. For the impact assessment the CLM-IA-baseline V3.02/World 1995 method, originally developed by Biewinga and Van der Bijl (1996) was used and calculations were done in SimaPro 8.04.30, Educational. Eighteen impact categories were analyzed but only the eight most relevant categories are presented (Table 5.3). Categories that did have insignificant or very similar results among cropping systems evaluated are not presented. However, the impact categories analyzed by the CLM method do not asses provisioning, supporting, or regulating services. Therefore primary productivity values either, mean seed or biomass yield or both were included for relevant cropping systems from Samarappuli et al., (2014), and Berti et al., (2017).

Calculated emission values were divided by the average seed or biomass yield of each sequence to indicate the global warming potential (GWP) by kg seed or kg of biomass (Table 5.3). All other impact categories, abiotic depletion, terrestrial acidification potential, eutrophication potential (freshwater and marine), ecotoxicity (fresh water, marine, and terrestrial), and human toxicity were estimated by the CLM-IA-baseline V3.02/ World 1995 impact method in SimaPro.

Abiotic depletion is defined as the use of non-renewable resources such as fossil fuels, minerals, and metals. However, estimation of abiotic depletion in LCA and impact analysis has not been void of controversy. Assessing the availability of natural resources is difficult and depends on both natural and economic stocks (Oers and Guinee, 2016). The abiotic depletion in this study was estimated by the CLM method (Biewinga and Van der Bijl, 1996). This method includes the exhaustion of fossil energy and mineral ores such as P and K, which are very important in agriculture. Methods for abiotic depletion are based on ultimate reserves as calculated from the average element concentrations in the Earth's crust (Oers and Guinee, 2016).

The input values indicated in Table 5.2 were added to the models and an analysis was run for each cropping system individually and then for the combined comparative analysis among all cropping systems.

Spider plots were constructed to integrate and graphically represent all environmental impact categories and ecosystem services of each cropping sequence. For this, all impact category values were normalized and transformed to a score between 0 and 1 (Schipanski et al., 2014). The greatest value in each category was assigned a score of 1 and all other values were calculated as relative to that value. Each axis in the spider plots represents one impact category or ecosystem service.

5.4. Results and Discussion

5.4.1. Global Warming Potential

Global warming potential results indicate systems that had maize, regardless of final use, either grain or silage, had the highest GWP values compared with other sequences, except for the sequence containing maize with forage sorghum as intercrops (Table 5.3). Sequences that contained soybean resulted in the lowest GWP values. This may be due to the higher use of N fertilizer in maize production compared with soybean which was not fertilized with N in this study. (Table 5.2 and Fig 5.2). Mineral N fertilizer production and transportation could result in up to 1.547 kg CO_2 eq of GHG emissions kg^{-1} of urea-N produced (Kopke and Nemecek, 2010). Higher N fertilizer application, can also lead to greater emissions of GHG in the field, such as N_2O emissions. Nitrous oxide has a GWP 298 times higher per unit of mass, compared with that of CO_2 (Kopke and Nemecek, 2010), and more than 50% of the GWP from crop production is due to the field emissions of N_2O (Audsley et al., 2009; Nemecek et al., 2015).

When comparing the conventional maize, to maize with cover crops in the previous fall that had less N inputs during the growing season, it was expected to have a lower GWP. But results indicate there was not much difference among conventional or maize with cover crops. Sequences with cover crops, needed additional seeds, sowing, and crop protection applications, thus additional CO_2 emissions due to increased diesel use. Kopke and Nemecek (2010) reported that a L of diesel fuel is equivalent to a kg of mineral N fertilizer, in GWP.

When comparing the GWP of the maize-forage sorghum intercropping (MFSS) with maize silage (MS) and forage sorghum (FSS), despite all systems had similar N inputs, MFSS showed a lower GWP to that of MS, but similar to that of FSS. This can be due to the less amount of crop protection used in FSS and MFSS systems, and may be also due to the lesser inputs needed to produce maize seed compared with that of forage sorghum. Sindelar et al. (2016), reported that sorghum is highly efficient in extracting soil N, thus the need for N inputs is relatively low. All systems that are designed for silage production had a high GWP contribution from harvesting (chopping), which was similar in all those sequences (Fig. 5.2).

Table 5.3. Impact categories of eleven cropping sequence/systems evaluated in North Dakota and Minnesota in 2011-2016.

Cropping sequence†	Global warming potential			Acidification	Eutrophication	Fresh water aquatic ecotoxicity	Terrestrial ecotoxicity	Human toxicity	Marine aquatic ecotoxicity	Abiotic depletion
	kg CO_2eq ha^{-1}	kg CO_2eq kg biomass^{-1}	kg CO_2eq kg seed^{-1}	kg SO_2eq ha^{-1}	kg PO_4eq ha^{-1}	---------------kg 1,4-DBeq ha^{-1}-------			Mg 1,4-DBeq ha^{-1}	GJ ha^{-1}
MG	1028	0.07	0.09	8.6	2.4	282	2.1	551	842	17.7
MS	1016	0.06	-	8.0	3.3	310	2.6	595	1285	16.1
SG	623	-	0.15	4.2	3.1	170	1.4	294	656	8.4
FSS	925	0.05	-	7.4	2.8	269	2.3	556	1203	15.0
MFSS	947	0.06	-	7.6	3.0	281	2.4	563	1218	15.2
MCG	1043	0.04	0.10	8.1	3.4	290	2.3	550	938	17.8
SCG	603	-	0.14	4.1	3.0	158	1.3	285	623	8.3
PMS	1037	0.09	-	8.1	4.1	331	3.0	608	1333	16.0
RMS	1008	0.09	-	7.9	3.6	327	3.1	590	1308	15.7
PFSS	930	0.05	-	7.4	3.4	282	2.6	563	1240	14.8
RFSS	902	0.06	-	7.2	3.0	278	3.0	545	1215	14.5

†MG=Maize monocrop (conventional)-grain, MS= Maize monocrop (conventional)-silage, SG= Soybean monocrop (conventional), FSS= Forage sorghum (conventional)-silage, MFSS= Maize-forage sorghum intercrop, MCG= Maize-camelina intersowing, SCG= Soybean-camelina intersowing, PMS= Cover crop (legume) in fall- followed by maize in spring, RMS= Cover crop (non-legume), radish, in fall followed by maize in spring, PFSS= Cover crop (legume) in fall followed by forage sorghum in spring, RFSS= Cover crop (non-legume) in fall followed by forage sorghum in spring

††Functional unit ha^{-1} yr^{-1} impact method CLM-IA-baseline V.3.02/World 1995.

§1,4 DB = 1,4-dichlorobenzene

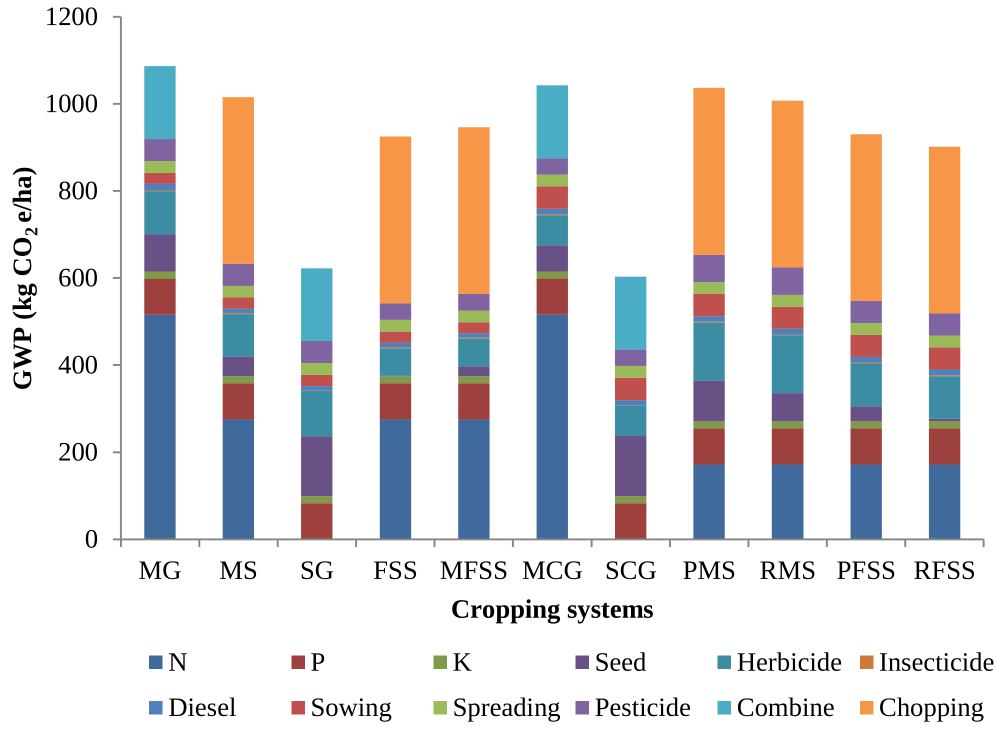

Fig. 5.2. Contribution to total CO_{2e} emissions by each input in each cropping system in the agricultural phase (cradle-to-gate). MG=Maize monocrop (conventional)-grain, MS= Maize monocrop (conventional)-silage, SG= Soybean monocrop (conventional), FSS= Forage sorghum (conventional)-silage, MFSS= Maize-forage sorghum intercrop, MCG= Maize-camelina intersowing, SCG= Soybean-camelina intersowing, PMS= Cover crop (legume) in fall- followed by maize in spring, RMS= Cover crop (non-legume), radish, in fall followed by maize in spring, PFSS= Cover crop (legume) in fall followed by forage sorghum in spring, RFSS= Cover crop (non-legume) in fall- followed by forage sorghum in spring.

When compared with maize for grain systems, which use ‘combining’ as the harvesting method, ‘chopping’ had a higher contribution towards GWP. This may be because, silage operations occur when plants have higher moisture content, compared with that of grain harvesting.

Equipment used for silage harvesting tend to move slower, and tend to carry higher loads which increase the diesel fuel use, thus increasing the GWP. According to Lazarus (2015), forage harvesters use higher amount of fuel h^{-1} in their operations compared with grain harvesters such as combines with similar horsepower.

When the GWP was calculated per product units (kg of seed and/or kg of biomass), the resulting pattern changed markedly (Table 5.3). Seed yield of soybean systems (SG and SCG) had a great impact in GWP when the functional unit used is kg^{-1} of seed ha^{-1}, compared with that of maize systems (MG and MCG). The analysis considered average seed yield for three environments, resulting 4.2 and 4.4 Mg ha^{-1} for SG and SCG systems, respectively and average seed yield for four environments of 10.9 and 10.5 Mg ha^{-1} for MG and MCG systems, respectively (Table 5.4).

This is expected since maize tends to produce greater seed yields compared with soybean for a unit area of land. Biomass yields resulting from maize systems that had a cover crop (PMS and RMS) in the fall, had a greater impact on GWP when the functional unit used is in kg^{-1} biomass ha^{-1} (Table 5.3), when compared with other sequences including maize. This is expected since PMS and RMS systems produced less biomass compared with other maize containing systems (Table 5.4).

5.4.2. Acidification Potential

Maize monocrop intended for grain (MG) had the highest impact on acidification with 8.6 kg SO_2eq ha^{-1} and soybean intersown with camelina for seed (SCG) was the lowest with 4.1 kg SO_2eq ha^{-1} (Table 5.3). As indicated before, soybean cropping systems had less N fertilizer than systems containing maize. Roer et al., (2012) reported that the highest impact on terrestrial acidification was caused by the production and use of mineral fertilizers volatilized as NH_3 or NO_x. About 15% of the N applied as urea can be lost as N-NH_3 to the air (Nemecek and Schnetzer, 2011). The impact method used (CLM) estimated acidification mainly based on NH_3 losses from urea (15%), but ammonia volatilization from urea varies with tillage, soil cover, temperature, plant uptake (Rojas et al., 2012), soil texture, pH, and soil water (Awale and

Chatterjee, 2017). Interestingly when comparing the MG with MCG which had identical seeding rates and fertilizer applications, there was increase (0.5 kg SO_2eq ha^{-1}) in acidification potential in sequences without camelina. This may be due to less amount of plant protection used in sequences that had camelina.

Table 5.4. Provisioning ecosystem services of 11 cropping sequence/systems evaluated in North Dakota and Minnesota in 2011-2016.

Crop sequence	Crop biomass yield	Crop seed yield
	------------------------------Mg ha^{-1}	-------------------------------
MG	25.1	10.9
MS	16.1	-
SG	-	4.2
FSS	17.7	-
MFSS	15.8	-
MCG	24.2	10.5
SCG	-	4.4
PMS	11.8	-
RMS	11.1	-
PFSS	18.7	-
RFSS	16.2	-

†Crop biomass and seed yield and energy efficiency were obtained from Samarappuli et al. (2014), Berti et al. (2017).
MG= Maize monocrop (conventional)-grain, MS= Maize monocrop (conventional)-silage, SG= Soybean monocrop (conventional), FSS= Forage sorghum (conventional)-silage, MFSS= Maize-forage sorghum intercrop, MCG= Maize-camelina intersowing, SCG= Soybean-camelina intersowing, PMS= Cover crop (legume) in fall- followed by maize in spring, RMS= Cover crop (non-legume), radish, in fall followed by maize in spring, PFSS= Cover crop (legume) in fall followed by forage sorghum in spring, RFSS= Cover crop (non-legume) in fall- followed by forage sorghum in spring.

5.4.3. Eutrophication Potential

Eutrophication potential levels fluctuated between 2.4 and 4.1 kg PO_4e ha^{-1} among systems evaluated (Table 5.3). Nemecek et al. (2015), suggested N fertilization could be correlated with eutrophication potential, however this evaluation contradicts that, where comparatively high N input systems such as MG and MS recorded a lower eutrophication potentials compared with low N input systems such as PMS. This may be due to the fact, the model did not account soil coverage for a longer period of time, reducing the potential for leaching, run-off, and volatilization, but considered only the inputs. The higher use of N fertilizers in maize and the period of time the soil is bare in late fall and early spring likely contributed to higher risk of N leaching and P run-off. In the USA Midwest, maize-soybean systems fall application of NH_3 liquid fertilizer are common. Although systems such as PMS use less N than maize, they had additional sowing and herbicide application operations, may be another reason that could partially explain the results. Nemecek et al. (2011), further argued that N leaching from mineral fertilizers can be lower since mineral N can be given at the time when the plant actually require it, compared with organic N such as from previous-season cover crops, that need to undergo mineralization first, which is a process greatly depend on soil and weather conditions.

Another interesting observation is that sequences including a legume cover crop tend to have a higher eutrophication potential when compared with the same sequence with a non-legume cover crop. Beaudoin et al. (2005) reported increased N leaching with legumes due to lower N uptake from fertilizer, shallow root systems, and presence of higher residual mineral N in soil. Mineralization of a decaying legume can release some of the N in the biomass as NO_3-N on the soil surface (Zotarelli et al., 2009). Furthermore, non-leguminous cover crops such as radish are known for their potential to scavenge nitrates from the soil profile (McSwiney et al., 2010). Eutrophication is also affected by P emissions through soil erosion to surface water and phosphate run-off. All cropping systems evaluated had similar P fertilizer rate, however the soil erosion potential and phosphate losses by run-off likely decreased in systems including intersown camelina, and cover crops due to the soil cover provided for longer time in the season.

5.4.4 Ecotoxicity

Fresh water, terrestrial, and marine water ecotoxicity results were higher in silage systems with maize monocrop than any of other cropping system (Table 5.3). Ecotoxicity increases with the use of more pesticides and also depend on the active ingredients in the pesticide (Nemecek et al., 2015). Soybean systems had the lowest ecotoxicity due to its low pesticide inputs compared with other systems in the study (Table 5.2).

Pesticides production contribution ranged from 12% (terrestrial ecotoxicity) to almost 30% (human toxicity) in the agricultural phase of maize in monoculture (Bacenetti et al., 2014). However, the increased biodiversity in maize systems with cover crops, intercropping with forage sorghum, and intersown camelina will likely lower the high selection pressure on insects, diseases and weeds, reducing the development of resistant types (Robertson et al., 2014), resulting in lower pesticide use in the long term. Reduction in pesticides can also contribute to lowering the GWP, since manufacturing of pesticides accounts for 3% of the GWP associated with crop production (Audsley et al., 2009).

5.4.5. Human Toxicity

Human toxicity results had similar pattern to that of ecotoxicity, where silage maize as a monocrop or in sequence with other crop were the highest, while sequences with soybean recorded the lowest values (Table 5.3). Similar to ecotoxicity, human toxicity mainly depend on pesticide treatments (Nemecek et al., 2015), which explains the results from the analysis.

However, Bacenetti et al., (2014), reported the contribution from urea production to human toxicity, and water and terrestrial ecotoxicity, ranged from 25% to 40%. Since all the systems evaluated in this study used urea as the N source, higher N inputs could likely increase human toxicity, but results did not support that.

5.4.6. Abiotic Depletion

Abiotic depletion includes non-renewable energy consumption, and mineral extraction, i.e. fossil fuels, metals, and minerals. Depletion of an abiotic resource indicates that its amount on Earth is reduced (Oers and Guinee, 2016). Abiotic depletion was highest in maize monocrop (MG) and for maize-camelina (MCG), systems intended for grain production (Table 5.3). Maize grain production depleted abiotic resources by 17.7 and 17.8 GJ ha^{-1} for MG and MCG, respectively, which in turn produced 10.9 and 10.5 Mg ha^{-1} of seed, respectively (Table 5.3 and Table 5.4). Systems containing soybean (SG and SCG), recorded the lowest abiotic depletion values among all systems evaluated. This can be explained by the higher use N inputs used in maize systems, compared with no N inputs in soybean sequences. Additionally, there was only a slight difference in abiotic depletion levels when comparing the monocrop to that of camelina intersowing sequence, in both maize and soybean. This can be expected since sequences with camelina did not receive any additional fertilizer. Li and Mupondwa (2014) indicated that abiotic depletion due to mineral extraction was very small for camelina, mainly due to the absence of P or K fertilizers.

Silage production, had less abiotic depletion potential compared with those of maize grain, mainly due to the less use of N fertilizer. Interestingly maize-forage sorghum intercropping (MFSS) had abiotic depletion values similar in range to forage sorghum (FSS), than that of maize (MS), regardless of similar fertilizer inputs. This can be due to maize seed production has high inputs compared to that of forage sorghum. The greater use of fossil fuels and minerals, including P and K fertilizers in high input systems such as maize explain the higher impact on abiotic depletion (Nemecek et al., 2011).

5.4.7. Integration of Ecosystem Services with Environmental Impacts

Spider or radar plots were used to visually demonstrate all environmental impact categories and some selected ecosystem services in all cropping sequences studied. For ecosystem services, biomass yield, and/or seed yield, values of 1 or closer to 1 indicate higher impact or higher productivity. Values were calculated as relative values of all cropping systems, i.e. in GWP maize-camelina intersowing system for grain (MCG) had the highest value so it was assigned a value=1, while all other systems had a value from 0 to 1 relative to the highest value. A value= 1 in GWP, abiotic depletion, acidification, eutrophication, fresh water ecotoxicity, terrestrial ecotoxicity, human toxicity, and marine water toxicity indicates the most negative impact, a cropping system have on the environment.

Both sequences including maize grain (MG and MCG), followed similar patterns in ecosystem services and environmental impact categories, except for eutrophication potential (Fig 5.3) as discussed before. Soybean sequences (SG and SCG) had similar patterns in all ecosystem services and environmental impact categories (Fig 5.4). Nemecek et al. (2015), suggested N fertilization is correlated with eutrophication potential and since soybean was not fertilized with N, any differences arising from additional sowing operation are small.

Winter camelina can take up as much or nearly as much excess N as winter rye (*Secale cereale* L.) (fall to spring) preventing run-off, when compared with both, conventional and no-till wheat-soybean systems (Ott et al., 2015). Intersowing winter camelina with maize or soybean, where camelina can act as a cover crop could decrease soil erosion by providing soil cover in the fall after cash crop harvest and in the spring before sowing the following cash crop (Berti et al., 2015). This period of time is where most soil erosion by wind occurs in the northern Great Plains (Van Donk et al., 2008). Camelina also has a high biodiversity score which is mainly due to early flowering in the spring attracting insects and other pollinators (Berti et al., 2017).

Maize for silage production and maize-forage sorghum intercropping (MFSS) resulted in similar biomass yield, but had less environmental impact than the sequences with radish (*Raphanus sativus* L) (RMS) or pea (*Pisum sativum* L.) (PMS) before silage maize (Fig 5.5). Nevertheless, cover crops and intercropping is expected to provide other benefits such as improving soil health, pest and disease suppression, and climate change mitigation (Zegada-Lizarazu et al., 2006; Lin., 2011). Yield stability and resilience of a cropping system will improve with the crop diversity, especially faced with adverse weather conditions (Gaudin et al., 2015; Sindelar et al., 2016). Considering the ability of forage sorghum to be more productive in environments with low fertility and less available water (Rooney et al., 2007; Undersander et al., 2010; Shoemaker and Bransby, 2011) compared with maize, intercropping of forage sorghum and maize would provide an option to have more resilient and stable, forage production system in the US Midwest.

Additionally, the model used to estimate GWP does not take in account that GHG field emissions are likely to be less when the soil is covered 12 months in a year in comparison with a monoculture that leaves the soil without cover for three to six months of the year. Schipanski et al. (2014) reported that having cover crops extended the time periods of C assimilation by approximately 8 months and soil cover by approximately 15 months over a 36-month rotation.

Forage sorghum after a legume cover crop (PFSS) resulted in the highest biomass in comparison with forage sorghum (FSS), but it was also the highest in eutrophication potential (Fig 5.6). Forage sorghum followed by a non-legume cover crop (RFSS) gave the highest terrestrial ecotoxicity among systems compared. Additional N provided by mineralization of the legume was probably the reason for higher biomass yield was higher, similar to that reported by Samarappuli et al. (2014). Similar to maize silage systems, the models did not account for additional soil cover provided by the cover crops, nor other potential ecosystem services.

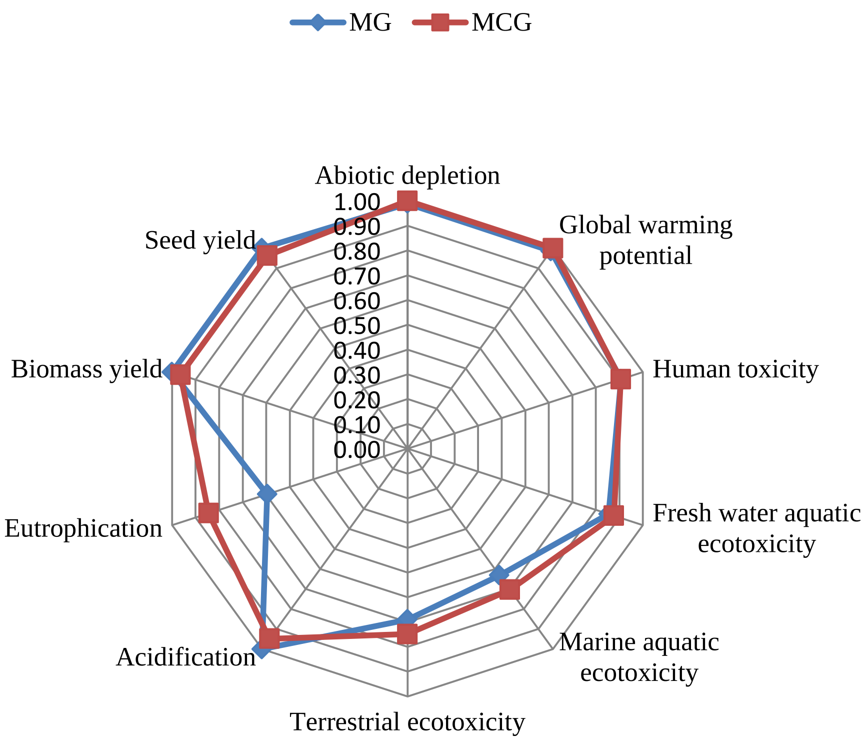

Fig. 5.3. Normalized values for eight impact categories and two ecosystem services averaged across two locations and 2-year sequence for maize monoculture for grain (MG), and winter camelina intersown into maize (MCG).

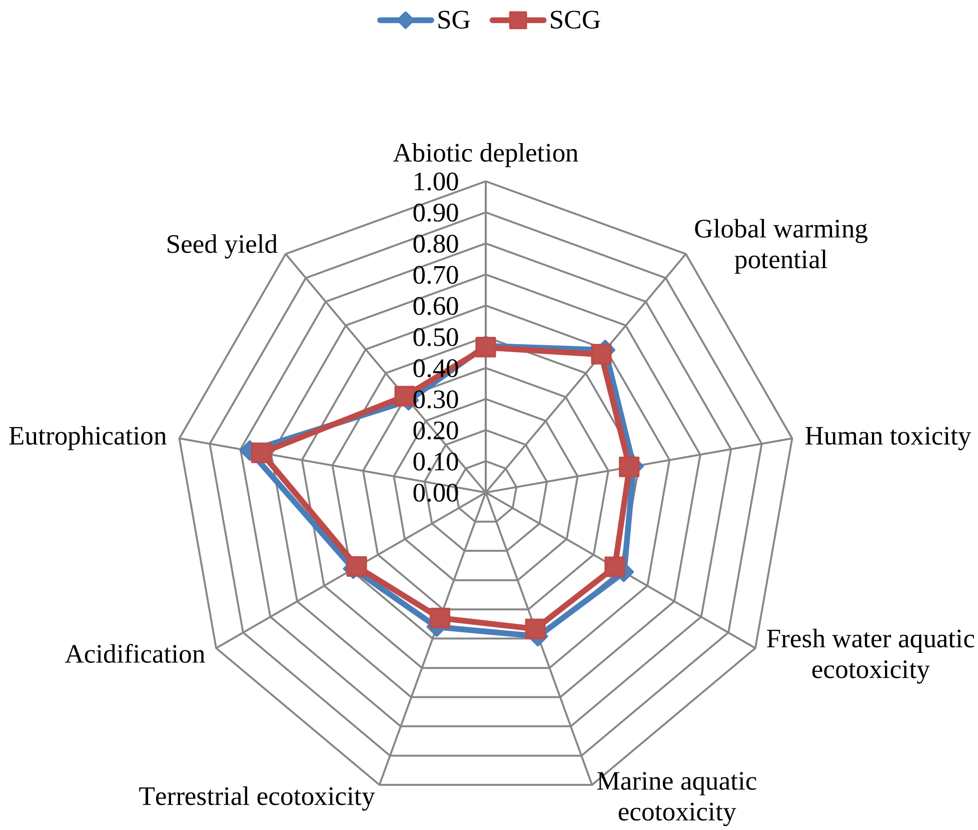

Fig. 5.4. Normalized values for eight impact categories and one ecosystem services averaged across two locations and 2-year sequence for soybean in monoculture (SG) and winter camelina intersown into soybean (SCG).

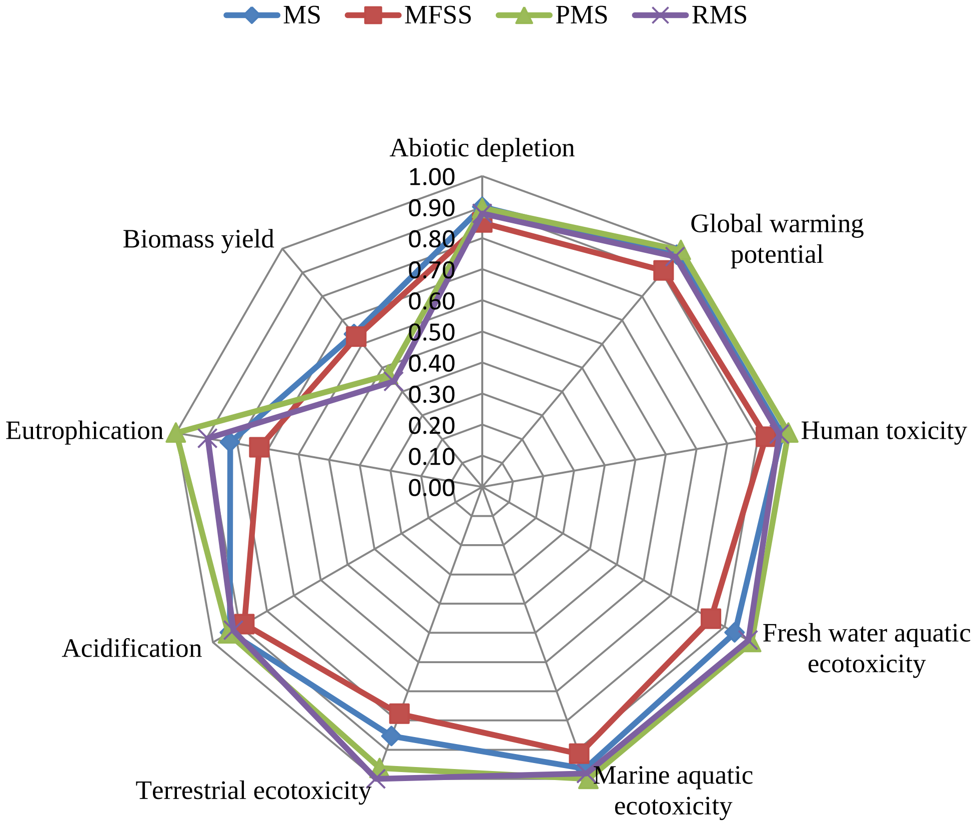

Fig. 5.5. Normalized values for eight impact categories and one ecosystem services averaged across two locations and 2-year sequence for maize monoculture for silage (MS), maize-forage sorghum intercropping (MFSS), legume cover crop followed by maize (PMS), and non-legume cover crop followed by maize silage (RMS).

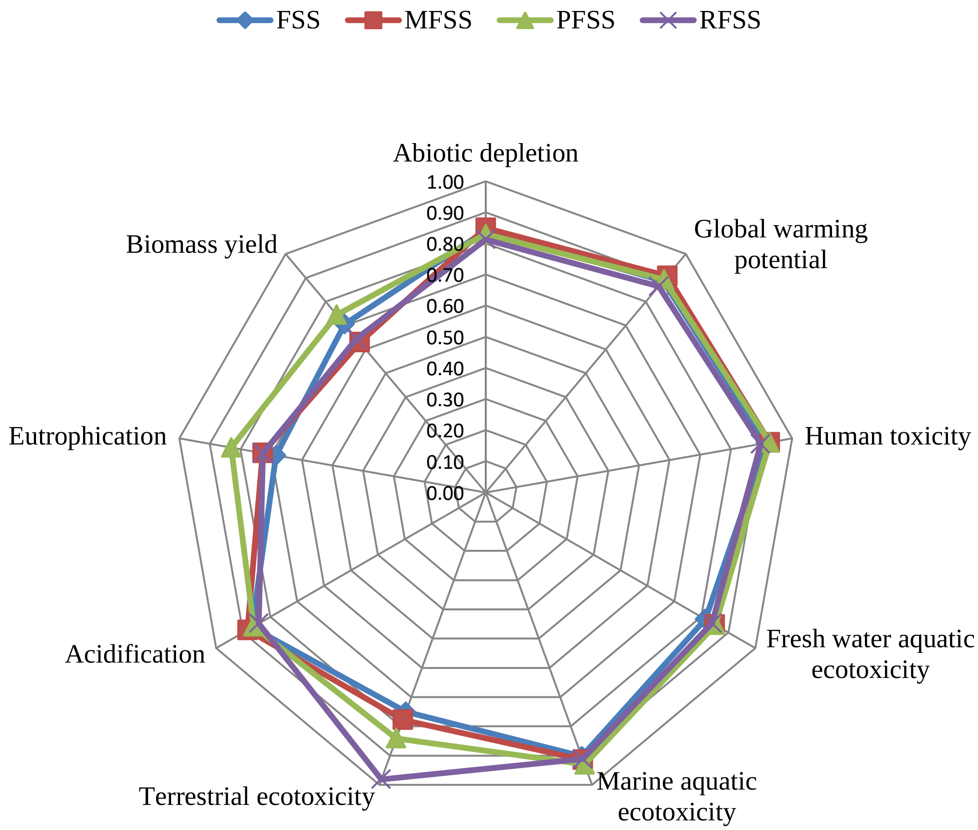

Fig. 5.6. Normalized values for eight impact categories and one ecosystem services averaged across two locations and 2-year sequence for forage sorghum monoculture for silage (FSS), maize-forage sorghum intercropping (MFSS), legume cover crop followed by forage sorghum (PFSS), and non-legume cover crop followed by forage sorghum (RFSS).

5.5. Conclusion

Cropping systems with high N fertilizer rates, additional inputs and processes contributed to high GWP. Considering maize and soybean monocrops which are common cropping systems in the area for grain production, intersowing of winter camelina had an environmental impact greater or similar to monoculture systems, mainly due to the additional inputs and processes required, compared with that of the monocrop. Although potential benefits might not offset the higher GWP, the incorporation of winter hardy cover crop such as camelina, will likely have long-term benefits to the soil health and biodiversity.

Intercropping maize with forage sorghum for silage production has the potential to provide comparable or better results in terms of providing biomass at a lesser environmental impact, compared with maize monoculture, in the US Midwest. Incorporating cover crops into crop rotations can offset some of the N inputs required by the subsequent cash crop, thus contributing to the reduction of overall GWP.

More research is needed to determine the impact of cover crops and winter camelina growth and soil cover in CO_2 and N_2O field emissions, in relation to N rates, soil water content, and temperature. Furthermore, having a green, photosynthesizing cover in the fall and early in the spring could partially offset CO_2 emissions but this too needs further research. Also, research is needed to assess all other ecosystem services these cropping sequences can offer when added to a rotation scheme.

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APPENDIX. BIOMASS YIELD, BIOGAS YIELD, AND FORAGE QUALITY PARAMETERS

Table A1. Mean biomass yield, plant height, N uptake, specific biogas yield (SBY), biogas yield (BGY), and plant tissue nutritional quality parameters at harvest for treatments containing grain maize (C1), silage maize (C2), forage sorghum (S1), and brachytic dwarf forage sorghum (S2) arranged as monocultures (C or S), and inter-row (C+S) and within-row (C x S) intercrops at Carrington, ND in 2013.

Treatment	Biomass yield	Plant height	N uptake	SBY	BGY	CP[†]	NDF	ADF	ADL	NDFD	TDN	RFQ
	Mg ha^{-1}	m	kg ha^{-1}	[†]$l_N kg^{-1}$ OM	Nm^3 ha^{-1}	------------------------------g kg^{-1}------------------------------						
C1	11.5	1.7	161.3	1048.8	11.7	86.6	536.3	291.4	53.7	758.5	666.2	154
C2	10.0	1.9	152.0	1085.3	10.5	95.2	541.2	291.6	51.8	753.9	664.6	157
S1	8.9	1.9	148.2	952.7	8.0	104.5	54.7	323.4	69.5	749.7	649.8	155
S2	9.9	1.0	171.3	1067.3	9.9	109.2	550.8	302.8	58.0	804.2	667.0	166
C1 + S1	9.9	2.0	163.3	949.3	9.0	103.1	499.3	274.5	50.4	741.9	684.3	172
C1 + S2	10.9	1.5	174.0	974.9	10.0	99.9	479.6	250.5	44.3	773.0	697.8	176
C2 + S1	10.5	2.0	168.8	1010.6	10.2	100.5	543.8	302.8	55.7	755.4	661.7	160
C2 + S2	10.3	1.4	168.2	1077.2	10.6	102.4	566.5	311.5	57.5	779.1	655.3	157
C1 x S1	10.2	1.9	158.3	1017.4	10.0	96.8	529.1	289.4	49.3	750.5	667.9	161
C1 x S2	9.8	1.7	155.7	996.3	9.4	100.4	499.9	269.9	46.9	776.7	686.2	171
C2 x S1	11.4	1.9	163.8	1004.7	11.0	91.1	567.3	318.2	61.8	748.1	649.6	150
C2 x S2	8.3	1.7	129.7	1044.7	8.3	98.2	547.4	300.6	53.5	789.9	662.9	159
LSD (*P*=0.05)	2.2	0.2	36.9	47.7	2.0	8.8	38.9	26.1	7.3	31.0	19.8	11

[†]specific biomass yield (SBY), biogas yield (BGY), crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), neutral detergent fiber digestibility (NDFD), total digestible nutrients (TDN), relative feed quality (RFQ).

Table A2. Mean biomass yield, plant height, N uptake, specific biogas yield (SBY), biogas yield (BGY), and plant tissue nutritional quality parameters at harvest for treatments containing grain maize (C1), silage maize (C2), forage sorghum (S1), and brachytic dwarf forage sorghum (S2) arranged as monocultures (C or S), and inter-row (C+S) and within-row (C x S) intercrops at Fargo, ND in 2013.

Treatment	Biomass yield	Plant height	N uptake	SBY	BGY	CP[†]	NDF	ADF	ADL	NDFD	TDN	RFQ
	Mg ha^{-1}	m	kg ha^{-1}	[†]$l_N$kg^{-1} OM	Nm^3 ha^{-1}	------------------------------g kg^{-1}---------------------------						
C1	18.1	2.1	227.2	997.0	17.5	78.4	480.4	257.4	53.3	713.9	696.5	160
C2	17.7	2.2	229.2	1073.0	18.4	81.2	508.7	276.5	43.4	728.1	682.3	157
S1	21.0	2.4	351.5	1015.9	19.7	104.6	572.1	325.9	72.3	701.3	638.8	149
S2	16.8	1.2	273.8	1028.2	16.2	102.9	529.3	292.8	62.8	749.0	666.4	163
C1 + S1	19.0	2.3	286.5	1031.9	18.5	94.2	521.6	283.0	56.1	683.7	671.6	160
C1 + S2	13.4	1.8	216.5	1001.5	12.6	101.4	467.0	246.7	47.2	740.1	701.9	178
C2 + S1	17.4	2.3	250.7	1017.2	16.9	90.5	542.4	301.7	59.4	726.8	663.9	156
C2 + S2	13.7	2.1	215.8	1044.2	13.5	99.0	509.2	279.1	47.3	743.2	676.8	166
C1 x S1	21.5	2.3	310.8	1001.5	20.5	89.6	541.8	301.9	61.0	713.6	660.7	154
C1 x S2	13.9	2.0	220.2	997.4	13.2	99.0	461.0	241.4	48.8	744.3	706.9	179
C2 x S1	19.2	2.3	275.8	994.5	18.2	90.3	530.3	297.4	56.1	719.5	664.9	156
C2 x S2	16.1	2.1	246.7	1041.5	15.9	96.6	495.5	268.1	46.2	729.2	688.4	170
LSD (*P*=0.05)	3.1	0.2	48.2	45.3	2.9	6.4	34.1	23.1	5.2	27.8	18.7	9

[†]specific biomass yield (SBY), biogas yield (BGY), crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), neutral detergent fiber digestibility (NDFD), total digestible nutrients (TDN), relative feed quality (RFQ).

Table A3. Mean biomass yield, plant height, N uptake, specific biogas yield (SBY), biogas yield (BGY), and plant tissue nutritional quality parameters at harvest for treatments containing grain maize (C1), silage maize (C2), forage sorghum (S1), and brachytic dwarf forage sorghum (S2) arranged as monocultures (C or S), and inter-row (C+S) and within-row (C x S) intercrops at Prosper, ND in 2013.

Treatment	Biomass yield	Plant height	N uptake	SBY	BGY	CP†	NDF	ADF	ADL	NDFD	TDN	RFQ
	Mg ha^{-1}	m	kg ha^{-1}	†l_N kg^{-1} OM	Nm^3 ha^{-1}	---------------------------g kg^{-1}---------------------------						
C1	13.9	1.7	170.7	1040.5	13.9	77.0	532.8	298.9	48.3	732.1	664.6	173
C2	17.2	2.1	223.7	1003.3	16.7	82.2	551.0	311.4	61.7	742.3	655.6	147
S1	21.0	2.6	358.5	997.9	19.8	107.6	579.6	337.1	66.3	706.4	634.7	148
S2	10.5	1.2	170.2	1050.8	10.3	102.9	564.0	321.4	59.1	760.6	648.6	148
C1 + S1	14.8	2.8	224.3	931.3	13.3	94.9	486.6	271.5	50.9	722.3	690.3	154
C1 + S2	14.7	1.5	212.7	942.4	13.3	90.5	485.5	270.3	47.7	736.5	688.9	170
C2 + S1	15.9	2.7	230.3	939.8	14.2	92.3	508.4	287.4	53.0	721.9	675.1	167
C2 + S2	13.5	1.8	219.7	957.0	12.2	101.7	481.5	268.9	43.2	747.1	687.6	161
C1 x S1	16.3	2.6	229.7	939.2	14.6	89.1	495.7	278.0	51.6	727.4	683.6	173
C1 x S2	16.6	1.7	225.8	908.3	14.5	84.8	442.7	238.0	47.0	694.5	707.1	164
C2 x S1	16.6	2.6	253.7	994.2	15.8	95.7	529.2	297.4	54.2	729.9	666.9	167
C2 x S2	11.8	1.9	189.7	976.1	10.8	100.3	483.2	265.8	46.2	753.6	691.0	160
LSD (*P*=0.05)	2.8	0.3	35.7	57.4	2.6	9.3	36.2	24.4	7.2	32.9	20.0	10

†specific biomass yield (SBY), biogas yield (BGY), crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), neutral detergent fiber digestibility (NDFD), total digestible nutrients (TDN), relative feed quality (RFQ).

Table A4. Mean biomass yield, plant height, N uptake, specific biogas yield (SBY), biogas yield (BGY), and plant tissue nutritional quality parameters at harvest for treatments containing grain maize (C1), silage maize (C2), forage sorghum (S1), and brachytic dwarf forage sorghum (S2) arranged as monocultures (C or S), and inter-row (C+S) and within-row (C x S) intercrops at Fargo, ND in 2014.

Treatment	Biomass yield	Plant height	N uptake	SBY	BGY	CP[†]	NDF	ADF	ADL	NDFD	TDN	RFQ
	Mg ha^{-1}	m	kg ha^{-1}	[†]$l_N kg^{-1}$ OM	Nm^3 ha^{-1}	----------------------------g kg^{-1}----------------------------						
C1	17.6	2.4	229.7	974.4	16.6	81.8	423.0	212.6	37.8	727.5	675.7	162.4
C2	19.6	2.5	262.3	1010.3	19.0	83.9	490.6	264.0	37.0	665.2	667.5	153.8
S1	22.0	2.7	334.0	867.5	17.8	95.0	577.9	343.3	62.6	639.7	641.1	150.7
S2	16.0	1.6	264.0	879.3	13.0	103.3	523.9	302.3	50.3	627.2	660.6	159.0
C1 + S1	16.3	2.5	247.7	951.8	14.9	94.6	502.9	271.2	48.8	676.6	682.0	161.7
C1 + S2	14.5	2.1	204.3	924.8	12.7	89.3	448.7	237.1	42.0	730.4	696.2	174.7
C2 + S1	18.6	2.6	261.3	967.3	17.2	88.4	502.0	269.1	45.4	671.8	666.9	160.9
C2 + S2	15.0	2.4	238.0	982.7	14.1	99.0	464.6	242.6	37.8	682.8	673.2	161.4
C1 x S1	21.2	2.5	310.3	936.3	19.0	91.3	495.3	269.5	46.7	679.9	670.7	162.3
C1 x S2	17.2	2.2	255.3	903.2	14.9	93.2	421.5	217.8	37.7	718.3	700.1	171.0
C2 x S1	21.9	2.3	317.0	958.1	20.1	90.3	478.8	252.8	43.1	678.4	660.4	157.6
C2 x S2	18.6	2.5	276.0	907.8	16.2	92.9	423.8	219.8	34.8	705.5	680.7	162.9
LSD (P=0.05)	2.9	0.2	47.2	53.3	2.4	7.7	37.3	25.7	6.6	29.4	19.5	10.4

[†]specific biomass yield (SBY), biogas yield (BGY), crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), neutral detergent fiber digestibility (NDFD), total digestible nutrients (TDN), relative feed quality (RFQ).